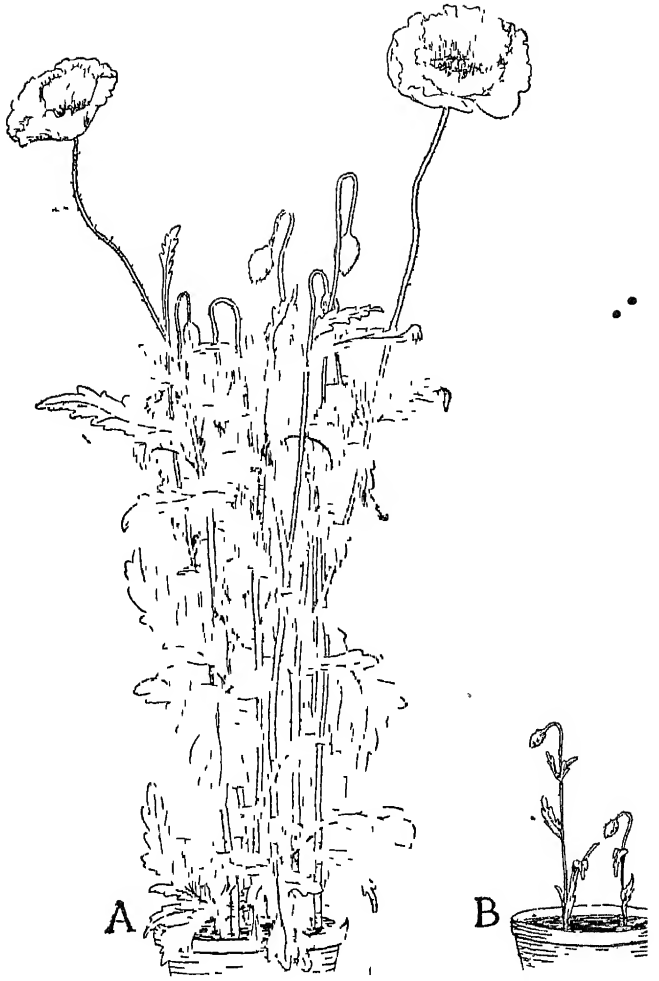

SAND CULTURES—POPPIES GROWING IN STERILE SAND

A Watered with normal culture solution B Watered with a solution lacking nitrates (See Chapter VIII) (From a photograph)

PRACTICAL
PLANT PHYSIOLOGY

BY

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PREFACE

The purpose of this book is to provide students and teachers with an outline of the experimental investigations on which our knowledge of the physiology of plants is based.

It would have been easier to present the most attractive of the facts and theories of this branch of science than to make the attempt, of which this book is the outcome, to provide a practical text-book which should serve as an educational instrument and as a stimulus to independent observations

The student, however, cannot grasp the facts of Natural Science by reading books on the subject Though the man of mature mind, trained in the art of sifting and grouping facts, and in the habit of seizing essential truths, may gain a useful acquaintance with Natural Science by the perusal of text-books, the student cannot He needs a method of education which serves, not only to furnish, but also to train the mind. In other words, the student requires both information and discipline He should be told less, and find out more It cannot be disputed that the element of intellectual discipline is ignored too much by modern educational methods, nor that, as a result, students suffer from lack of training

In science, in particular, the teacher is too much concerned with rendering the subject attractive and too little with making it to serve the end of developing the reasoning and imaginative faculties of his pupils

The method of teaching Natural Science by means of lectures and a ritual of practical work associated therewith is fundamentally wrong It appeals to the memory but

sterilizes the imagination It preaches comfortable f to the student, who ought, instead of being submitt scientific sermons, to be experiencing the process, at pleasurable and painful, of teaching himself

In the course of the lecture hour, the teacher cov large area of ground which is a terra incognita to student From the fulness of his experience, the le clears the ground of all difficulties which beset the of the scholar, with the result that the latter, thoug may, or may not, have enjoyed the personally-condu tour, has learned nothing of the art of exploration student would be unable, indeed, to find his way over the same ground if left to take the journey alon

Subjected to this lecture-method of instruction, student becomes the repository of the second-hand W he is told to look for, he sees with the teacher's eye the method is successful and the student docile, the l passes his examination with distinction, but remain ignorance of the importance of initiative The less d student takes and expresses—often by idleness a st dislike to science, preferring, instinctively, some sub more calculated to train the mind or less certain to over the memory

In either case, the lecture-method, which dates from time when books were scarce, or dear, or bad, accompli little in comparison with what might be achieved if ground were traversed during the lecture-excursion a the student, instead of being told things, was encour to observe and think for himself

Until the present, deplorable method is replaced l better, Natural Science, which must come in time to an essential part of all educational curricula, must sub to the reproach of being of less value, as a subject mental training, than Mathematics or Classics The proach is not deserved Without a knowledge of Nat Science, men and women remain blind to half the be and meaning of life without it, they are ignorant of modes whereby all manner of pressing problems, soc political and other, ought to be attacked if they are to solved

If reform is to be effected in the teaching of Nat

Science, it must be by making the subject less an affair of information and more a matter for thought The logical argument which runs through the Natural Sciences, cohering the innumerable facts to a whole, must be displayed, and the student must find, in his scientific studies, means of developing the higher functions of his mind, namely, the powers of thinking rightly and imagining freely

The proper method of teaching Natural Science is as follows Very young children should be rendered familiar with large numbers of natural objects, including, of course, plants and animals The purpose of this preliminary course is to make the child take cognisance of natural objects and phenomena, of flowers and their names, of fruits and seeds, of buds and leaves, of herbs and trees In short, confining our remarks to the biological side of this course, the child should learn by means of it to see and watch and care for some of the myriad living things of field, hedgerow and garden

This is the Nature Study course, in which no attempt should be made to force explanations or to develop the reasoning faculty of the child, the object being to furnish the mind

Having achieved this end, Nature Study has exhausted its educational service It is as useless in later stages as it is valuable in the early stage of education

The Nature Study course should be succeeded in the school by one on elementary physics and chemistry Such a course is, as a fact, followed in many schools In it, the properties of matter are first investigated experimentally, and, later in the course, the relations of facts or phenomena, one with another, are studied During this course, the child begins to reason and to imagine scientifically

There should follow the third part of the course in Natural Science, which should be of a biological nature

It is a great misfortune that this third part but rarely finds a place in the school curriculum The scholars continue too long with the more mechanical Natural Sciences, Physics and Chemistry, and leave school only too often with no knowledge of Biology

This is the case generally with boys, though, not infre-

quently, girls follow a course of morphological Botan instead of one on Physics and Chemistry

In either case, the results are bad Neither the bo nor the girls know anything of the modes of life of plan or animals, the boys, because they have not studied t subject, the girls, because, without a knowledge of t elements of Physics and Chemistry, they cannot understan it The remedy is to require the scholars, boys and gi alike, to follow the elementary course in Physics an Chemistry, and then to proceed to one on the elements Biology.

The object of this book is to provide such a biologic course, that is, one suitable for the higher classes schools and for the first year class in the University

It is true that the book deals only with the physiolo of plants, but it is true also that anyone who is famili with the facts of this science knows not a little of t essentials of animal-physiology

By following the course, the training in reasoning an in imagination, begun during the study of Physics an Chemistry, is extended The scholar who has pass through the three courses outlined above possesses confident knowledge of the most important facts of Natur Science He has also a trained mind

This book is useless as a reading-book, but, if i intention has been fulfilled, it should prove a serviceal tool wherewith the student may dig out for himself t fundamental truths of the science

To do this means, of course, hard work on his par but once the student has learned that one of the chi pleasures of life lies in hard, intellectual work—just another great pleasure lies in the hard, physical wo which he bestows on his games—he will, it is to be hope prefer this course to the easier, sitting-down metho wherein he plays the part of a recipient of knowledge which he knows neither the origin nor the mode of gettin

If the book is to serve the end for which it has be designed, it must be used, like any other tool, in a prop way

The teacher should decide on the number of chapte which are to be dealt with in any special course I

should then divide the chapters into lessons, each of which should be accomplished in the hours which may be devoted to the subject in the course of the week Having explained that the need for making one experiment follows from the conclusions drawn from its predecessor, the teacher should point out to the students that they should pay no attention to the results of any experiment recorded in the text-book until they themselves have obtained records

Before starting an experiment, the student should read the instructions both in the text and in the appendix, so that he may know all the details necessary for the setting-up and use of the apparatus Having done this, the student should make, in each case in which the experiment admits of it, a working drawing of the apparatus which he proposes to construct, and he should write a brief prediction of the results which he expects to obtain by the performance of the experiment When the apparatus is made, and before he begins to use it, the student should examine it critically with the object of making sure in advance that the apparatus can do the work required of it Should the apparatus fail to work properly, the student must submit it again to critical examination in order to discover the cause of the failure

Nothing is more valuable for the education of students than learning to construct apparatus, making it work, discovering the reasons of its failure and devising means for overcoming its defects

Instead of expending his energies in lecturing, the teacher should devote himself to obtaining material suitable for the experiments, assisting students in overcoming difficulties and securing permanent records of the experiments These records should be deposited in the physiological museum, to which frequent reference is made in the text

When a lesson is completed, the teacher should discuss the results and conclusions with the students, and point out the bearing of these results on other parts of the subject

In conclusion, though the author must be held responsible for any errors which are contained in the book, and for the opinions expressed in the preface, he acknowledges

with pleasure, what is acknowledged already in th
page, that, in writing this book, he has had the adv
of the assistance of his colleague, Miss M C Ray

Nearly all of the illustrations have been made ex
for this volume Some are reproductions from
graphs, others are due to the skill and kindness c
Dorothea Richardson, from whose original drawing
have been reproduced

FREDERICK KEI

University College, Reading,
December, 1910

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CHAPTER I

THE problems of plant physiology and the method by which they to be solved The scientific method Classification of physiolo problems

A SEED sown under suitable conditions germinates, giv rise to a seedling The seedling grows, puts forth lea and branches, drives its roots further and further into soil, and becomes a mature plant Presently and in season the flowers appear, endure in their delicate bea for a while, and, their work being done, fade away T stalks which bore the flowers now support the swell fruits within which the seeds are ripening When seeds are set, the fruit bursts open, scattering them and wide, or, falling to the ground and rotting, sows seeds near the parent plant Such are the more striki episodes in the life of a flowering plant

This regular sequence of events—the germination of sown seed, the formation of roots and branches, leaves a flowers, the setting of the seeds and the ripening of fruits—seems so natural that we are apt to accept it needing no explanation But when we begin to obser the several processes more closely, to reflect upon them, to compare one plant with another with respect to them, find ourselves asking all sorts of questions Why is it t the chickweed of the hedgerow runs its course from se ling to fruiting stage in less than one brief season, whils foxglove does not reach the flowering stage till its seco year? By what gymnastic exercises does the seedli extricate itself so neatly from its seed coat? How is it t the plantain on the lawn hugs the ground so closely as escape almost uninjured the knives of the cutting machin

Whence come the power and the material by mean which the giant oak with gnarled trunk and sprea branches forms itself from an acorn? How is it that matter which way up we plant a bean seed in the soil root of the seedling turns downward and burrows in earth, whilst the stem twists itself so that it comes to g upward into the air? From what source does the obtain the sugar to which it owes its sweetness or the the perfume with which it scents the air?

When once we begin to interest ourselves in plants find that the problems which they suggest are as varie they are numerous, and we realise that in every plac hedgerow, field, or garden, all sorts of strange event happening

Could we but find answers to the questions which h plants suggest to us, we should be in possession of a g body of knowledge concerning their life and work other words, we should have taught ourselves not a of the science of plant physiology

Hence the most pressing of our problems is, how we to set about obtaining answers to any of the ques which arise in our minds when we observe living pla Curiosity suggests the problems, how does science to solve them?

In order to find out the method of scientific disco let us fix our attention on some particular phenom exhibited by a plant, and consider how we may asce its significance

The phenomenon which we will choose for investig is the origin of the drops of water which appear or leaves of certain plants, such, for example, as the

1 † We sow oats in ordinary soil in two pots, and, the leaves of the seedlings are four or five inches in he we may find, on examining them in the early morning, near the apex of each leaf is a shining drop of w looking like a dew-drop (Fig 1)

We want to discover whence the water-drops come Though we were to sit up all night watching the pl we should obtain no solution of the problem all we sh

† The numerals, in heavy type, which occur throughout the book re the experiments which are to be performed, see Preface, p xi

see is that the drops, when first formed, are small, and that they may increase in size very rapidly. Observation, therefore, though it provides us with scientific puzzles, does not

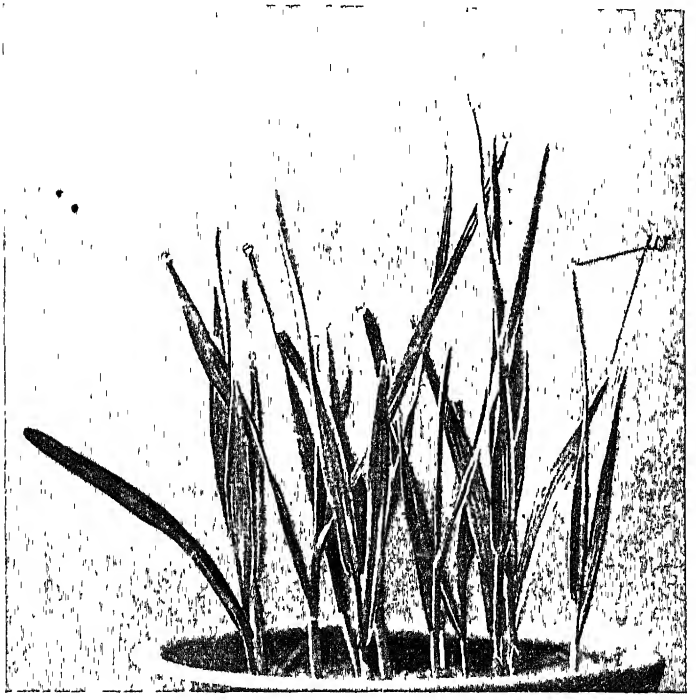

FIG. 1. OAT SEEDLINGS

Drops of water (w), excreted from water pores (hydathodes) in the tips of the leaves
From a Photograph

necessarily help us to solve them. Observation, careful and continued observation of the living plant, is essential for the study of plant physiology, but something besides observation is wanted now.

Evidently all we can do is to make a guess as to the origin of the water-drops. Confronted with the problem,

we call imagination to our assistance, and by its aid gu
at the answer As the result of guessing, we suggest t
the water may be dew formed from water-vapour in the
Next we ask ourselves, suppose the guess is wrong, w
then? At once common-sense makes answer, if the wa
does not come from the air, it must come from the plan
self Having exhausted our guessing powers, we proc
to look coldly at the alternative suggestions, and to rev
them in the light of common-sense In this case, comm
sense admits that either guess may be right But
guesses cannot both be right Therefore we must disco
some way of deciding between them If the problem w
one of a kind with which we are more familiar, for exam
as to the height of a friend, and if two people gues
differently with respect to this, we should not hesitate
to our method of verification We should stand the fri
against the wall and measure him That is, we sho
put the guesses to the test of experiment Whereas
amount of discussion would determine the correctness
the guesses, a yard measure properly used would se
the matter in a minute

In like manner, to solve the problem of the origi
the water-drops, we submit it to the test of experim
But how is this to be done? Once again we must app
to imagination and common-sense We must use th
faculties conjointly in order to invent an experimental t
In our particular problem, it is easy enough to devis
method We know that plants take up water from
soil, and so we argue thus if the drops of water on
leaves come from the air, they may make their appear
as readily on the unwatered as on the watered plants,
if the drops come from the plants themselves, it
probably matter fundamentally whether the plants con
much or little water Thus we arrive at our metho
experiment Water one pot thoroughly, withhold w
from the other, and examine the plants on succes
mornings When we do this, we find that the water-dr
are plentiful on the leaves of the watered seedlings,
are absent from, or, at all events, fewer on the others

To complete the proof we devise a further experimen

2 For example, give water to the previously

watered pot, stand it under a bell jar, and observe that in five or ten minutes drops of water appear on the tips of the leaves. Therefore we conclude that the water which appears on the leaves comes from the plant and not from the air.

But in solving the particular problem, we have discovered also the answer to the general problem—how to set about getting replies to special questions? The answer is—by using exactly the same method as that which we have just employed. There is indeed no other way. It is called the scientific method, and involves, as we have learned, processes of guessing, reasoning, and trying.

Thus the processes involved in the use of the method are as follows:

1. The guessing process, in which the imagination is invited to suggest possible answers to the problem under investigation. Our guesses may be as wild as we like to make them. The more the imagination is allowed to run riot, the more likely are we to open up new paths for investigation. Indeed, it is no exaggeration to say that the greatest discoveries are the outcome of the wildest guesses.

2. The judging process, in which common-sense assumes the part of adviser, recommending this or that guess as more likely to prove true, and rejecting any guess which runs counter to established truth.

3. The testing process, which consists in the devising and execution of experiments calculated to demonstrate the truth or falsity of the guess, or, as it may be called, the hypothesis, which gains the approval of common-sense.

4. The summing-up process, by which we decide, whether the evidence provided by the results of the experiments is convincing or not.

If the evidence is absolutely conclusive in favour of our hypothesis, we speak of that hypothesis as a fact, if the evidence is inconclusive, we may yet continue, for want of a better, to hold the hypothesis and to use it in our arguments, though in doing this we have to be extremely cautious, and to remember that our hypothesis is 'not proven."

Hence to study a science aright is not to become a narrow

specialist, but to develop all the highest faculties of the mind. This scientific method is not peculiar to plant physiology; it is the method employed in all the sciences, and by its use all the knowledge of nature which we possess has been obtained.

All that remains to be done in this introductory chapter is to classify our problems, that is, to arrange those of like nature in groups, and the groups in convenient order. In doing this we will make an assumption which may not, at first sight, seem very probable, but which will be of great service to us. Whether the assumption is true or false we shall discover as we proceed with our investigations. We assume that the life of a plant is not different in essentials from that of an animal or from that of man himself. Unless this assumption is wholly false, and, in that case, we shall soon discover our mistake, it will be of great assistance to us in the otherwise puzzling problem of the arrangement of our questions. For we know, without the aid of science and from our common experience, a good deal about our own life-processes. We know, for example, that we feed and that without food of certain kinds we cannot live. We know that we breathe, and that we cannot exist for more than a few minutes without air. We know also that we, like animals in general, move, and that some movements as, for example, getting up in the morning, depend on an effort of will, whilst other movements, for example, the beating of the heart, are independent of consciousness. We know also that animals and plants grow, give birth to young, and ultimately die.

Hence we arrive at the following classification of the problems of plant physiology:

(1) Feeding processes (nutrition)
(2) Breathing processes (respiration)
(3) Growth processes
(4) Phenomena of movement and of sensitiveness (or irritability)

CHAPTER II

THE mode of germination of seeds the parts of the seed and seedling the resting and active states of seeds the resisting powers of resting seeds . germination capacity the visible order of events in germination The nature and function of cotyledons and of endosperm adaptation in plants large seeds and small seeds

A FULLY grown plant is by no means a convenient subject for experimental purposes Not only is it bulky, but its roots are hidden in the ground and cannot be disturbed without damage to the plant On the other hand, a handful of pea or bean seeds may be obtained for a penny, and, when planted, the seeds produce seedlings in the course of a week or two Moreover, inasmuch as the seedlings grow rapidly, we may assume, from analogy with young children, that they are likely to feed hungrily Hence seeds and seedlings should prove very useful to us in our studies in plant-nutrition We will therefore commence our work by an examination of seeds and seedlings

Since we shall require seeds for all sorts of experiments, we must take every opportunity of getting together a large and varied collection At the proper times of the year, ripe seeds of garden plants, weeds, and common trees should be gathered, dried, and stored in corked or stoppered bottles The bottles should be labelled, and on each label should be written the name of the seed (or fruit), the locality whence it was obtained, and the date of gathering If it is not possible to collect a sufficiently varied assortment of seeds, some may be purchased from seedsmen and stored in labelled bottles Samples of the seeds and fruits should be affixed to cards with the name, natural order, and other interesting details, such, for example,

as locality and weight, and the cards placed in t physiological museum, in which records of expe ments, specimens, and photographs, etc , should be kep In case the beginner does not know how to distingui seeds from fruits—and some fruits look exactly like see —he should refer to an elementary text-book (Bibli graphy, 3, 5), which deals more particularly with t morphology of plants, that is, with the characters a peculiarities of their form and structure For, though w in studying the work of plants—that is their functions shall have to take notice of their form and structure, w have not space to deal fully with the morphological bran of botany

Having become familiar with the shapes, sizes, a peculiarities of the seeds and fruits of the common plants, we proceed to germinate some peas At once t question arises since the seeds in our collection do n germinate whilst in the bottles, what is to be done in ord to make them begin to grow? Now everyone who h access to a garden or to the country knows how quick weeds and other plants spring up in showery weather, a hence we make the sure guess that a supply of water necessary for germination Even though we know thi we prove it, for, by so doing, we shall extend our know ledge and make it more precise

3 To this end, prepare three pots of garden soil, d one thoroughly in a kitchen oven, and, in order to preve the soil from getting moist again, set it to cool under a inverted marmalade jar, or similar vessel See that th soil in the other two pots is thoroughly moist Determin the average weight of ordinary, dry pea seeds by weighi several samples of twelve each Put a couple of doze seeds to soak in tepid water, and, after twenty-four hour dry their surfaces by means of a cloth, weigh and compa them with respect to weight, size, and shape with the d seeds Calculate the percentage of water taken up No plant four or six peas in each of the three pots puttin dry seeds in the pot with the dry soil, dry seeds in on of the pots with moist soil, and soaked seeds in th remaining pot Label the pots 1, 2, 3, and note in a roug note-book the details of time of planting, and states o

seed and soil Cover each of the pots with a glass plate or piece of cardboard or stiff brown paper, and see that the soil in pots 2 and 3 does not get dry Record the dates of appearance of the seedlings in each of the pots Copy out the results neatly in a note-book kept for the purpose, and add any remarks that seem interesting Records should be made of the results of every experiment that is performed, and, whenever it is useful, sketches should accompany the records, which should be arranged in brief, tabulated form

4 Take the remaining soaked seeds, wipe them, put them in a dry place—for instance, on a shelf in a living room—and weigh them at daily intervals, and thus determine the rate at which they lose water When they seem fairly dry, put them in a thin paper bag in a desiccator (See Appendix V) At the same time, weigh and place in a paper bag a dozen dry, unsoaked peas, and put this bag, properly labelled, in another desiccator After an interval of about a week, weigh the two lots and determine how much each has lost in weight Leave them exposed to the air of a room for some hours, weigh them again, and compare these weights with those of the same seeds when taken from the desiccator From the experiments, it is evident that seeds are hygroscopic, that is, they take up water from moist air and give up a certain amount of water when the air to which they are exposed is dry The bearing which these facts have on such matters as the following should be considered —the importance of storing seeds out of contact with moist air the difference that the weather at the time of harvesting is likely to make to the viability of the seed the advantage and possible disadvantage of soaking bean or pea seeds before sowing in the garden the fact that, in wet autumns, seeds of various plants may be found germinating whilst still attached to the parent plant

In cases where students work in groups, some should use one kind of seed for the above experiments and others another, *e g* barley grains (which are strictly fruits), horse chestnuts, onion seeds, etc The results obtained with these different seeds should be compared with one another

We have now confirmed our knowledge that seeds,

in order to germinate, require water, we have four that the amount of water which seeds, such as peas, ca absorb is surprisingly large, and we have learnt als that seeds are hygroscopic We recognise that a knov ledge of these facts helps us to store our seeds properl and shows us how we may hasten their germination W will next determine whether seeds dried as thoroughly a possible in a desiccator are absolutely dry, or whether the still contain water

5 To this end weigh a dozen peas which have been i the desiccator for a week, soak them till they are soft, wip them with a cloth, and pound them in a mortar, transfe the whole of the mash to a weighed, dry porcelain dish and dry it thoroughly in a drying oven at about 100° C After two days, take the dish out of the oven, stand it in desiccator to cool, and then weigh it Replace the dis in the oven and continue the weighing at daily interva till no further loss of weight is recorded We thus obtai the *dry weight* of the substance of the seeds, and a compar son of this weight with that of the desiccator-dried seed tells us how much water the latter, apparently dry seed really contained The result of the experiment proves th. even the driest seed contains a considerable percentage o water The above experiment will be the more instructiv if, at the same time, other vegetable tissues, *e g* carrot turnips, and also fresh leaves (grass or spinach, etc) ar weighed, dried in a desiccator, weighed again, then choppe up (there will be no need to soak them first, as they ar not so flinty hard as the seeds), pounded in a morta dried in the drying oven, and then dry weights determine

6 A ready way of proving that ordinary air-dry seed contain a considerable amount of water is as follows ha fill a wide-mouthed glass bottle with peas Stopp the bottle, and place it in the drying oven at abou 90-100° C After 1-2 hours remove the bottle and obser that, as it cools, water, given off by the peas, condens to form drops on the sides By using different kind of vegetable tissue it will be discovered that they a contain a certain amount—some a very large amount- of water, and that, of vegetable structures, seeds conta far less water than any others That it is to this la

that seeds owe their resistant powers we demonstrate in the following way

7 Prepare a saucepan of boiling water, place a few ordinary dry peas and equal numbers of soaked and of desiccator-dry peas in small canvas or muslin bags, plunge them in the boiling water for a few seconds, plant the three lots (after soaking the dry seeds) in pots, and record their germination. Whereas the thoroughly dry seeds have not been injured by their short immersion in boiling water, the soaked seeds show by their failure to germinate that they have been killed. It is noteworthy that advantage is taken of the resistance of dry seeds to high temperatures in treating grains of oats, the surfaces of which are suspected to be contaminated with the spores of a disease-producing fungus called smut. The grains are plunged for five minutes in water at a temperature of 55°C., and subsequently sown. The effect of the hot water is to destroy the smut spores without injuring the oats.

8 Next, the effects of low temperatures on very dry and on soaked seeds should be determined. The most convenient way to do this is to pound up ice and salt and to put the freezing mixture into a small pail, in the middle of which a glass flask is placed. The several small lots of peas, each lot in a muslin bag, are put into the glass vessel and left there for some hours. The bags of seeds are then withdrawn, and the germination capacities of the three lots of seeds tested.

From the result of this and similar experiments it is learned that dry seeds are more resistant to adverse conditions than soaked seeds.

During the summer we make a comparison between unripe and ripe peas. Definite experiment is not necessary to convince us that the unripe seeds in their young pods contain far more water than the ripe seeds, and we may take it that, during ripening, one process which goes on is the gradual loss of water by the seeds. When, on the one hand, we call to mind the extremes of temperature to which the seeds of plants are exposed during their long winter's sojourn in the ground, and when, on the other hand, we realise the great resistant power of dry seeds, we cannot doubt that this natural drying process, which

takes place during the ripening of seeds, is of advant to the plant, making undoubtedly in many cases difference between destruction and survival That resting state is due, in large measure, to the natural dry during ripening may be inferred from the experiments have made, and also from the fact already noted that, wet autumns, various kinds of plants may be met w the seeds of which are already beginning to germinate the parent plants Specimens illustrating this phenome should be collected and added to the museum

Experiments recently made have proved that certa seeds may retain their capacity for germination for a gr number of years, in one instance, among seeds known have been kept for 87 years, some were found to be capa of germination, and it is interesting to know that expe ments are now in progress to determine for how lo seeds, which have been dried as thoroughly as possible, w retain their vitality Though, as we have just learn dry seeds may survive for many years, there is no evide to prove the truth of the statements which are often ma that wheat grains and seeds of other plants deposited thousand or more years ago with mummies in mum cases in Egypt have retained till the present day th powers of germination Indeed, there is good reason believe that such "mummy wheat" has long ago lost vitality

Our experiments demonstrate that a seed is a structu which, by reason of its dryness, is capable of passi through a long resting stage Whilst in the dry sta it is far more resistant than is the growing plant providing it with water, the seed may be caused to p from its resting or latent state into one of activity Wh is true of seeds is also true of the simpler reproduct bodies of many of the lower plants For instance, it h been shown that the resting spores of some bacteria a not destroyed by exposure to such high temperatures 100°-120° C., at which temperatures the bacteria in th active, growing state are killed That this great power heat-resistance is due to the dryness of the spores is prov by the fact that, if the spores are brought under such co ditions of moisture and warmth that they begin to gro

they lose their resistant powers Since the group of plants known as bacteria includes many disease-producing forms, and since some of the latter produce resting-spores, the bacteriologist and the doctor have to take the resistant powers of spores into account in their efforts to exterminate disease-producing germs

Let us now return to our study of seeds, and set ourselves to find out what is the first visible sign of germination

9 In order to do this sow samples of soaked seeds, some in earth, others in germinators Germinators of various patterns may be obtained ready-made (Appendix B), but one of the simplest and most useful may be made from a couple of ordinary saucers Several layers of thick white blotting-paper are moistened thoroughly and fitted neatly into one saucer A few soaked seeds are distributed on the blotting-paper, and the other saucer, into which moist blotting-paper may also be fitted, is inverted over them The only precautions necessary are that the blotting-paper should not be too wet to begin with nor become too dry The saucers may be covered with a large jar or box and stood in a warm place Every second day, two or three soaked peas are put into the germinator in order that we may obtain all the various stages of germination at one and the same time In the course of a day or two, a small white conical structure is to be seen projecting from the first sown seeds It elongates to form a cylindrical body with a rounded end By comparing older with younger stages, it will be seen that this body or, at all events, the greater part of it is the young root or radicle This method of making comparisons backward, that is, of comparing an older with a younger structure, is very useful, and will often enable us to determine the nature of doubtful structures Whilst the pea seeds are germinating, drawings should be made of each stage up to the time when the various parts of the seedling are recognisable Germinate also a number of other seeds, *e g* mustard or cabbage, onion, etc, in order to demonstrate that what is true of the pea is true of other seeds, namely, that the root is the first member to make its appearance We

might indeed have guessed that this would prov be the case, for it is by the root that the plant fixes in the soil, and it is an essential condition for the majority of flowering plants that they should be f "rooted" in the soil

The next stage in germination may be seen in seedlings, the radicles of which are about an inc length In such seedlings, a curiously looped stru makes its appearance One end of this structure is tinuous with the radicle, the other end is still in the Gradually the loop lengthens and ultimately its free becomes visible This free end, when looked at thr a pocket lens, presents a somewhat plume-like appear the parts corresponding to the feathers being small, g flat structures, the smallest of which are very minute wrapped round the tip of the looped body By comp this with later stages, it is evident that the looped l which soon straightens out and points upward, is the s and the small green structures, which arise as outgro from it, are the leaves This seedling stem, with its m leaves, is called the plumule Following it down towards the radicle we find that, at a certain point, are attached to it, on either side, two stalks If we re the seed-coat from the seed of a germinated pea, we cover that the part of the seed which was enclosed separates into two halves, and that each part is conn with one of these stalks The two, massive, more or hemispherical bodies, which are connected by stalks the stem of the seedling, are called the cotyledons sently we shall have to find out what they are and they have this peculiar shape

The different parts of the seedling have received diff names Not is this unnecessary, for it facilitates parison between different seedlings and enables t appreciate the fact that, despite their great differen shape and size, large numbers of seeds and seedling built on the same fundamental lines That this is so be seen by comparing the seeds and seedlings of the radish, and sycamore, illustrated in Figs , , and

Each of these seedlings consists of a shoot and a (radicle) The shoot is made up of a leaf-bearing

which terminates in a bud (the plumule). That part of the shoot which lies above the insertion of the cotyledons is called the epicotyl, and that part which lies below the cotyledons and merges insensibly into the root is called the hypocotyl. In some plants, e.g. pea, the epicotyl makes up nearly all of the mature shoot-system, the hypocotyl remaining short, in others, e.g. radish, the epicotyl grows but little. Throughout its first year, it remains very short, and produces a rosette of leaves arising from about the ground level. The hypocotyl, on the contrary, increases considerably in length, and, with the root, forms the edible part of the radish.

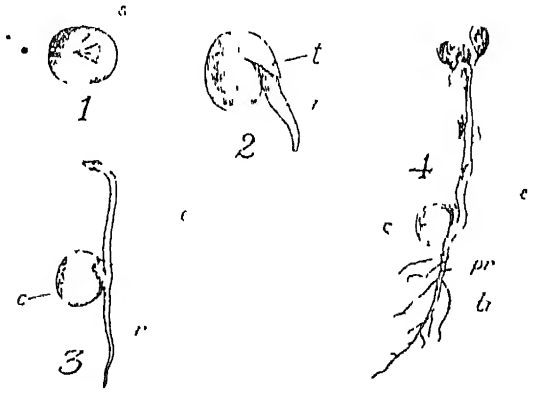

FIG. GARDEN PEA (PISUM SATIVUM). SEED AND SEEDLINGS.

1, Seed; 2, 3, 4, Seedlings, in three successive stages of germination. s, Seed; t, testa; c, cotyledon; r, radicle; e, epicotyl; pr, primary root; b, lateral root.

By comparing such very different seedlings as those of the pea, mustard or turnip, the castor-oil plant, etc., we reach the conclusion that similar parts are present in each, though they are developed to different extents in the different plants.

We have now to investigate the nature of the two large, lobed bodies which, as we have seen (p. 14), are attached each by a stalk to the stem of the seedling. By re-

moving the coat of a soaked, ungerminated pea o bean seed we find that, on pressing gently on th seed along the edge opposite the radicle, the white fleshy mass shows signs of separating into two halves If we insert the point of a pen-knife in the split we

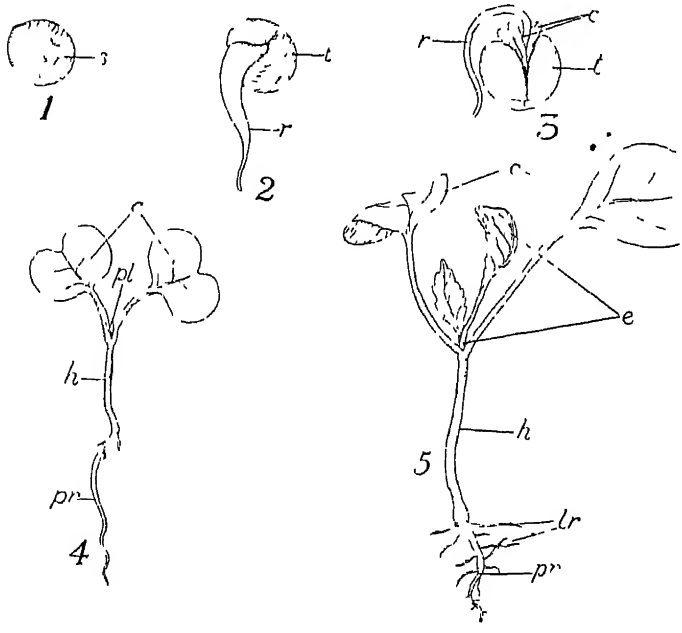

FIG 3 —RADISH (RAPHANUS RAPHANISTRUM) SEED AND SEEDLINGS

1 Seed 2, 3, 4, 5 Seedlings in four successive stages of germination s, seed, t, testa, r, radicle, c, cotyledon, pl, plumule, h, hypocotyl, e, epicotyl, pr, primary root, lr, lateral roots

can, without tearing anything, force the two halves apart and see, by the aid of a lens, that the epicotyl, though small, is already formed, and lies pressed close to the inner surface of one of the two fleshy bodies, which we recognise as the cotyledons Hence the seed of

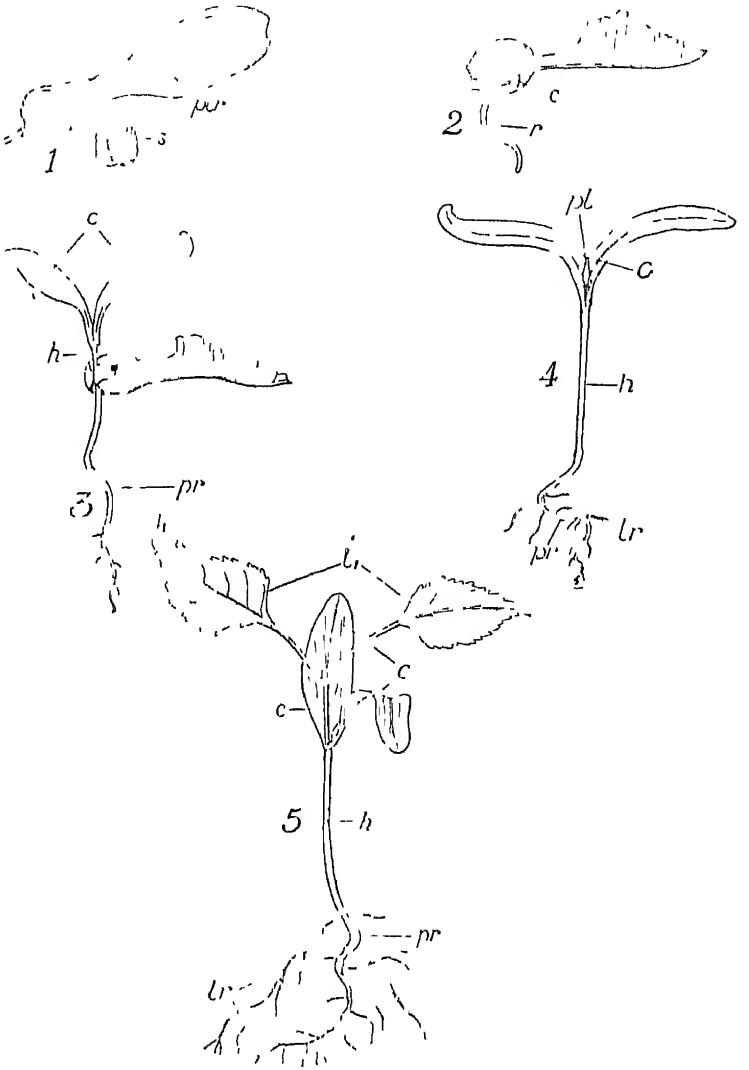

FIG. 1

SYCAMORE (ACER PSEUDO PLATANUS) FRUIT, SEED AND SEEDLINGS

1 Half fruit (median) seed removed 2, 3, 4, 5 Seedlings in four successive stages of germination *per*, perianth, *l*, first foliage leaves, other lettering as in Fig 3

the pea consists already of a miniature plant with epicotyl, hypocotyl, radicle, and cotyledons attached to the stem at the junction of epicotyl and hypocotyl The whole embryo, as the plant in the seed-stage is called, is enclosed in a seed-coat, which, except for a minute hole (micropyle) at the place where the root will emerge, forms a continuous envelope about it The structure of the pea or bean seed is now clear, except in one particular We recognise in the embryo all the parts present in the young plant with the exception that nothing comparable with the cotyledons occurs in the latter We must therefore attempt to discover what the cotyledons are, and what are their particular functions

First, we will see whether we can find out something about the cotyledons by examining the young pea or bean-plants which we have raised from seed

Dig up a plant which is from six inches to a foot high, and, observing that the remains of the seed are still attached to the stem, remove the seed-coat and note the shrivelled cotyledons Sometimes we may see that a bud or even a small branch springs from the angle (axil) which the stalk of a cotyledon makes with the stem If we do not find such axillary buds or branches, we have a ready means of causing them to grow large enough to be seen, namely, by preventing the growth of the main stem

10 Thus, having selected a seedling bean-plant about three inches in height, growing in a pot or in the open, cut away or pinch off the stem at the ground level After some weeks, we note, on digging up the plant, that the two shoots which have formed arise, each in the axil of the stalk of a cotyledon Now take a branch of a tree and examine it to see how its lateral buds and branches arise They will be found, in the vast majority of plants, to occur only on the stem just where a leaf is borne, in other words, lateral buds are borne in the leaf-axils We may argue thus, lateral buds and the branches which they produce arise in the axils of leaves a lateral bud, which develops to a branch, arises in the axil of a cotyledon therefore the cotyledon is a leaf But such an argument, to be convincing, requires to be supported by other evidence Let us therefore see if further evidence is to be

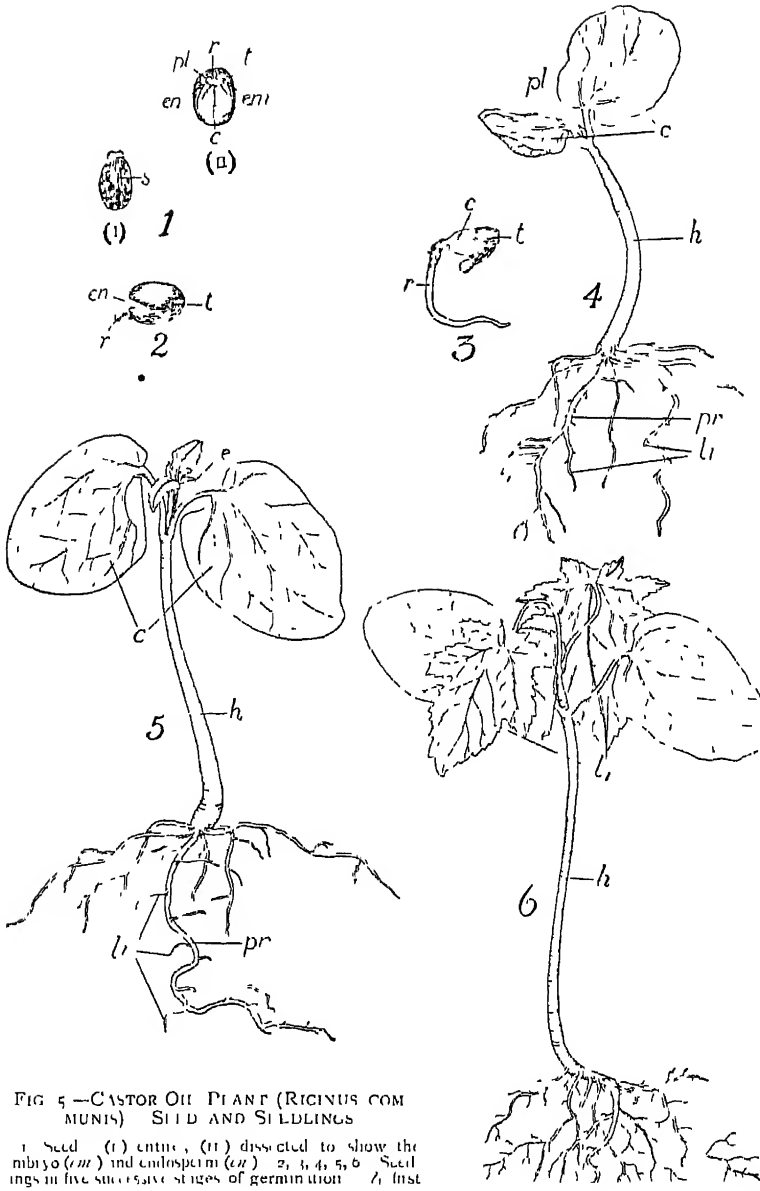

FIG 5.—CASTOR OIL PLANT (RICINUS COMMUNIS) SEED AND SEEDLINGS

1 Seed (I) entire, (II) dissected to show the embryo (*em*) and endosperm (*en*) 2, 3, 4, 5, 6 Seedlings in five successive stages of germination *l*, first

found The kidney bean (Phaseolus vulgaris) is very lik the broad bean (Vicia faba) They both belong to th same family, and are likely, therefore, to be similar in the essential characters

11 Sow three or four kidney beans and study their ger mination It will be found that they make no concealmer of the foliar nature of their cotyledons, for, as germinatio proceeds, the cotyledons are drawn out of the seed-coa borne upward above the ground, turn green, spread out fla and show themselves to be leaves Cotyledons which ris above the surface of the ground are said to be epigean those, *e g* of the broad bean, which remain below th ground, are termed hypogean

As an exercise in observation—and observation require exercise and frequent exercise for its development—deter mine the nature of the cotyledons of the castor-oil plan (Ricinus communis, Fig 5), firstly, by dissecting carefull soaked seeds after removing their coats, and, secondly, b observing germination-stages

It remains to find an answer to the question —why admitting that it is a leaf, is the cotyledon apt to depart s much from the conventional form of leaves?

12 If, during early spring, we look at a lilac o privet bush just when the buds are breaking, we fin that the outer leaves of the bud, though green an like the inner leaves, remain small, and may fall off a the bud grows to form a branch But if we cut awa the top of the bud with its group of very young leave just after it has opened, the outermost leaves, whic normally remain small and fall away, grow into ordinar foliage leaves (museum) Now repeat the observatio and experiment on the buds of the flowering currar (Ribes sanguineum) By dissecting away the leaves o the just-opening bud and laying them out in order o a sheet of paper, we see that they form a series which when we read it backwards, from the innermost to th outermost leaves, comprises fully-formed foliage leave consisting of blade, stalk, and leaf-base, leaves, th base of which is well developed and the blade only jus recognisable, and leaves consisting of leaf-base only (se Fig 6) These last never grow into ordinary leaves, and

having served the purpose of protecting the bud during winter, are cast off on the opening of the buds in spring (museum) From these examples we learn that a plant-member, such as a leaf, may be constrained, according to the need of the plant, to change its function We learn

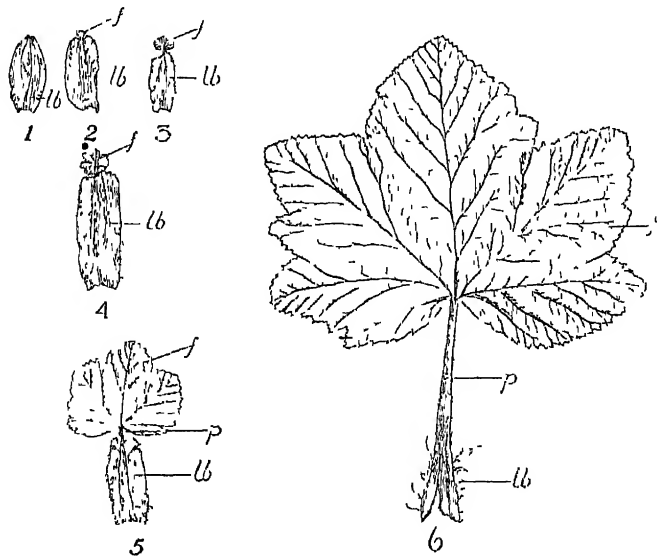

FIG 6 —FLOWERING CURRANT (RIBES SANGUINEUM)

1, 2, 3, 4, 5 Series of leaves from opening bud, showing transitions from scale leaf (1) to foliage leaf (6) *lb*, leaf base, *p*, leaf stalk, *f*, blade

further that when the function changes, the form may also change

Many important facts follow from this conclusion For example, it is evident that the particular form assumed by a leaf, or stem, or root, has some relation with the kind of work it has to do Hence, just as we infer when we see a sharp-edged tool, that it is used for cutting, so, when we have had some general experience of the kinds of work to which the different parts of a plant's machinery are

put, we are able to infer from a departure from the norm usual form displayed by a member of the plant-body th that member is charged with a new, unusual duty. Th power of adjusting means to ends is possessed by plan and animals to an extraordinary extent, and is spok of as adaptability, the modification being called an adapt tion. The power of adaptation by which an organis may modify the function of an organ and effect chang of structure and of shape serving to fit the organ f its new work, should be studied by the student suitable seasons of the year. For example, he shou determine the morphological nature of the tendrils of pea plant, asking himself, are these structures stems, leaves, or parts of leaves, or roots? When he has solv this morphological problem, let him ask himself wheth this departure from the normal structure fits the org for the work it has to do. Among the innumerable subjec for such morphological exercises we may mention pota tubers, opening buds of beech, onion or hyacinth bulb strawberry runners, and double flowers (stocks, rose etc.), but the best subjects are those which the stude discovers for himself. The method he must use is th of comparison. He must compare the thing with itself different stages of its development, *i.e.* he must study i developmental history or embryology, and he must com pare the thing with its nearest allies, *e.g.* a double flow with a single flower of the same species—a garden ro with a wild rose, and so on. This is the method of com parative anatomy, which may be pursued further and ma to include microscopic as well as a naked-eye investigatio

Now to apply our conclusions to cotyledons. In som plants, the foliar nature of the cotyledons is obvious, *e.* ir plants of the cabbage tribe—turnip, cress, cabbage, et —and in the castor-oil plant, etc., in others, though n apparent at first, it becomes so during germination, *e.* kidney bean, in yet others, *e.g.* the pea, bean and hors chestnut, it is by no means apparent. Keeping in mind t cases of the buds of the lilac or privet and of the flowerin currant, we surmise that the reason why some cotyledona leaves have retained their foliar character whilst othe have, in large measure, lost it, is that the former ha

retained the functions of ordinary leaves, and that the latter have exchanged these functions more or less completely for others Change of form is an outward and visible sign of change of function What then is the new function which the thick, unleaf-like cotyledons of the pea have assumed? When the castor-oil seed was dissected, the student must have been struck by the fact that the embryo did not take up the whole of the space within the seed-coat He saw that, covering the thin, delicate seed-leaves (cotyledons), which lie pressed together in a plane median to, and parallel with the flatter surfaces of the seed, there is a mass of soft, white tissue This tissue, called endosperm, from which the castor oil of commerce is extracted, has no counterpart in the ripe pea or bean seed On the other hand, whilst the cotyledons of the pea and bean are thick and unleaf-like, those of the castor-oil seed are thin, and so leaf-like as to show even their "veins" Let us state the facts thus —Castor-oil seed, cotyledons thin and leaf-like, a mass of tissue (endosperm) external to the embryo making up the larger part of the seed Bean seed, cotyledons fleshy, no corresponding endospermous tissue external to the embryo, the seed-leaves making up the larger part of the seed If we could discover the use of the endosperm to the seedling, we could make a good guess why the cotyledons of the bean are fleshy Conversely, if we could find out what purpose is served by the fleshy cotyledons, we should know probably why the castor-oil seed contains endosperm Again, as always, when confronted with problems in plant-physiology we have recourse to our scientific method of guess and experiment Now it cannot have escaped our notice when we were germinating various kinds of seeds that some are small and produce small seedlings, and some are large and produce large seedlings If we examine seeds of the latter kind, we see that they have invariably either large and fleshy cotyledons or much endosperm, and if we dissect seeds of the former kind we find that the cotyledons are thin and that, if any endosperm is present, the amount is but small

As a study of the museum specimens shows, the size of a seed has a relation with the size of its cotyledons

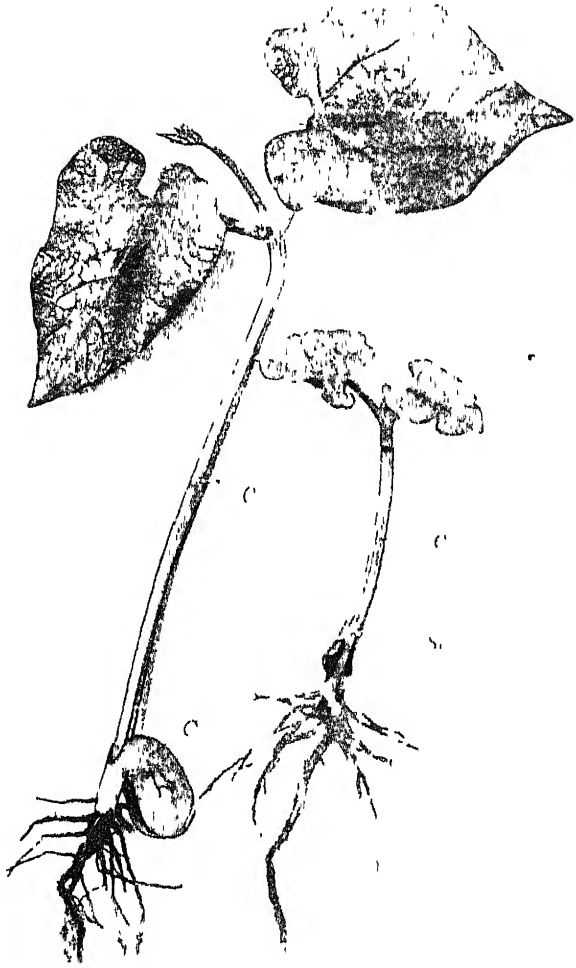

FIG. 7.—KIDNEY BEAN (PHASEOLUS VULGARIS)

From a Photograph

A, Seedling germinated under normal conditions. B, Seedling germinated at the same time as A, but from which the cotyledons were removed at germination. *c*, cotyledon; *e*, epicotyl; *Sc*, scars left after removal of cotyledons.

or endosperm, and not with the size of the mature plant which it produces Moreover, a large seed produces a large seedling, and a small seed a small seedling. We can scarcely doubt that the big seedling is due in some way to the big cotyledons or to the large amount of endosperm, and, thinking of the effect which proper feeding has on the size of young animals, the idea dawns upon us that perhaps the large cotyledons and the endosperm contain food supplies on which the seedling is enabled to feed during germination This hypothesis we can put to the test If it is true, then, as the seedling grows, the cotyledons should be found to shrivel and the endosperm to disappear We have already seen the shrivelled cotyledons of the young bean plant (p 18), and so have some confirmation of the correctness of our hypothesis

13 To obtain complete proof we may proceed to weigh the shrivelled cotyledons of a bean which is about a foot high After drying them in a drying oven, we compare their weight with that of the cotyledons of ungerminated bean seeds, similarly dried We find that the dry weight of the shrivelled cotyledons is considerably less than that of the fresh cotyledons of ungerminated seeds Another and more striking method as soon as the epicotyl appears in each of six kidney bean seedlings sown in germinators, remove, by means of a sharp knife, the cotyledons from three of them, and plant all six seedlings in a pot with garden soil Determine the rate of growth of the two sets (Fig 7) Record draw and preserve one plant of either set for the museum (For this purpose the plants may be dried between blotting-paper and mounted on cards) A similar experiment may be made with maize or wheat seedlings, in which case it is the endosperms which must be removed (cf Fig 8) The result in either case is the same The seedlings formed from the seeds deprived of their fleshy cotyledons or of their endosperm, though they grow, increase in size much more slowly than those from intact seeds Whence we conclude that endosperm and fleshy cotyledons serve as reservoirs of food-materials on which seedlings draw for their nutrition Presently (Chapter III) we shall have to enquire into the nature of these food-materials and how the seedling obtains them

It is interesting and typical of the ways of living t that the same end, in this case that of endowing the ling with a capital of food wherewith to start in life, be secured by different ways the one, by convertin

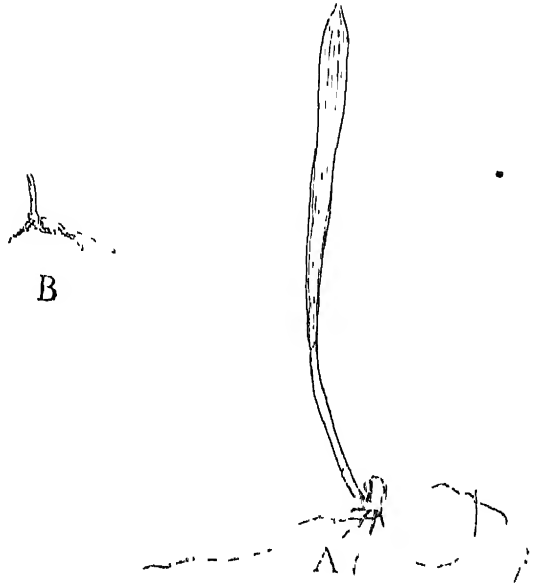

FIG 8 — WHEAT (TRITICUM VULGARE)

Showing the relative size of seedlings grown with and without nourishing pe

A Seedling, germinated on moist blotting paper. B seedling of the same germinated under similar condition, except that the endosperm was removed b germination began

seed-leaves into storehouses, the other, by the pro of a separate, nutritive tissue (endosperm) external embryo In point of fact, the difference between with, and seeds without endosperm only amounts to that the embryo of the endospermous seed waits it begins to grow before taking up the provision of material made for it by the parent plant, whereas

embryo of the seed without endosperm takes up the food-substances and stores them in its cotyledons before it ripens and comes to rest. If the parent makes a liberal provision, the cotyledons become thick and fleshy; if the provision is niggardly, the cotyledons remain thin and the seed is small. With a knowledge of the meaning of big cotyledons and large masses of endosperm, we obtain an understanding of the significance of the great variability of seed-production shown by different plants. The parent plant provides the material out of which the tissues of the cotyledons or endosperm and embryo are formed. The parent may produce either many small seeds or fewer large seeds: compare, for example, the poppy and pea. The one or the other habit runs in plant-families, and it is interesting to note that, of two of the most successful plant-families, the members of one, Leguminosae (peas, beans, clover, vetches, etc.), produce large and relatively few seeds, those of the other, Compositae (daisy, dandelion, etc.), produce small and relatively many seeds. We can also understand that the work of seed-production entails a certain amount of exhaustion to the parent plant, and that, therefore, a copious crop of seeds and fruits one year may use up so much of the food-material at the disposal of the parent that but few, or even no seeds may be produced the following year, *e.g.* beech, etc. So much is this the case that there is a great group of plants which die after once flowering. To this group belong our annual garden plants and weeds which live for one season or less, produce seed and die. If they are prevented from flowering, their lives may be prolonged, as any one with a garden or even a space for pot-plants may prove for himself. Not all once-flowering plants, however, are annuals, various tropical or sub-tropical shrubs and even trees grow for many years and ultimately flower, set seed, and die (*e.g.* species of aloe, palms). Other plants are biennials, that is, flower in their second year (turnip, carrot, foxglove), whilst others again are perennials, and may live for centuries and flower again and again.

Having accomplished our objects, of learning something of the general nature of plants and of beginning our studies on nutrition, we will conclude this chapter with

the remark that the pea or bean type of seedling its axis terminating above in a plumule and belo radicle and bearing two cotyledons laterally, i only type of seedling to be met with among flo plants If we call this type the Dicotylous type, v say that there is another, very varied type, v

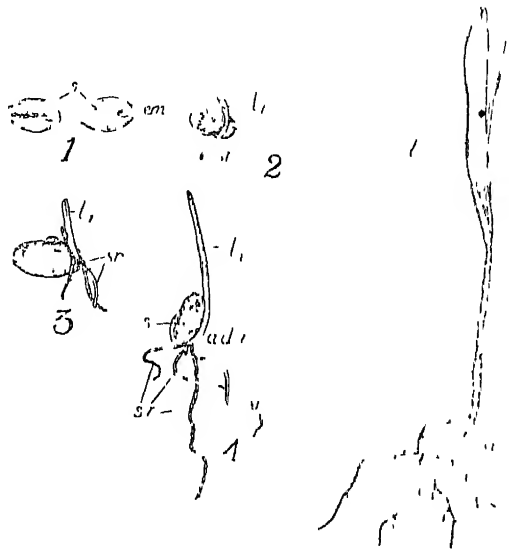

FIG 9—WHEAT (TRITICUM SATIVUM) [illegible]

1 Grain of wheat (z, fruit enclosing one seed) [illegible] successive stages of germination x, fruit, cz, endosp[illegible] coats of fruit and seed, c, [illegible] system, l_1, l_2, l_3, 1st, and 2nd leaves

Monocotylous type Seeds of the latter, wheat, oats, barley, maize, and date, should be [illegible] germinated, their seedling stages studied, and pr in the museum (Fig 9) Some help will be [illegible] in making out the parts of such seeds as these, h may be obtained from a text-book of general (Bibliography, 3, 5)

CHAPTER III

The nature and chemical properties of the food substances contained in the cotyledons and endosperm of seeds

When we reflect on the results of our observations and experiments on fleshy cotyledons and on endosperm, we are bound to be struck by the fact that those seeds which contain large quantities of food-material serving for the nutrition of the seedlings are also the seeds which are used most largely by man and animals for food. When cereal crops are ripe, that is, when the plants have transferred stores of food-materials to the endosperm of the seed, man intervenes and, gathering in the crop, makes flour from the grains. Flocks of birds anticipate man, and by their depredations bring serious loss to the farmer. Teeming populations in the East support life solely on rice, the seed-like fruit of a grass (*Oryza sativa*). The oilcake on which cattle are fattened is derived from the remains of the reserve-materials of the seeds of rape, cotton, etc. Thus the conclusion impresses itself upon us that the food materials of the seedling serve also as food for man and animals. That this is so, will add interest to our present enquiry into the nature of these food-materials and the way in which they are used by the seedling. Since a thorough examination into the chemistry of the food-materials, or, as we may call them, the reserve-materials of the seed, involves both a knowledge of chemistry and also the occasional use of the microscope, and since some students may lack the necessary chemical knowledge or be unskilled in the use of the microscope, we will indicate by means of an asterisk (*) the experiments which may be omitted by beginners.

14 Soak one or two wheat or barley grains in
when soft, cut them in halves, and smear some of th
endosperm on a saucer or porcelain slab add a few
of a solution of iodine dissolved in water with pot
iodide (Appendix A), note that a blue colour is pro
Obtain some finely powdered, pure starch from a cl
repeat the potassium-iodide iodine test (1) by add
solution direct to the powder, (2) by first boiling a
the starch with water in a test tube or beaker, then c
the boiled liquid with several times its volume of
and, after cooling, adding the iodine solution If

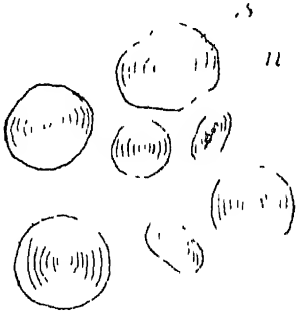

FIG 10.—STARCH GRAINS FROM THE ENDOSPERM OF BARL
n, hilum of grains; *s*, lines of stratification due to different
successive layers

blue liquid, note that the colour disappears cool
the tap, note that the colour reappears We thu
mine that the blue colour obtained in the p
experiment is due to starch We speak of this rea
a test for starch, or as the *iodine reaction* for starch

15 * Scrape the cut surface of a soaked barley
barley grain with a clean knife, transfer a little
scrapings to a small drop of water on a glass sli
on a cover glass and examine the preparation at fir
a low and then with a high power of the microscope
several starch grains, indicating the characteristic
centric markings (Fig 10)

16 * Cut sections through the endosperm of whe

cotyledons of the bean and the tuber of the potato Note the positions of the starch grains, groups of which lie in the compartments of which these tissues are composed Draw Run in under the cover glass of one of these microscope-preparations a drop of potassium-iodide iodine solution Note the blue or blue-black colour of the grains Crush soaked wheat grains in a mortar with a little water, transfer some of the pasty mass to a test-tube shake well and filter through a filter funnel lined with filter

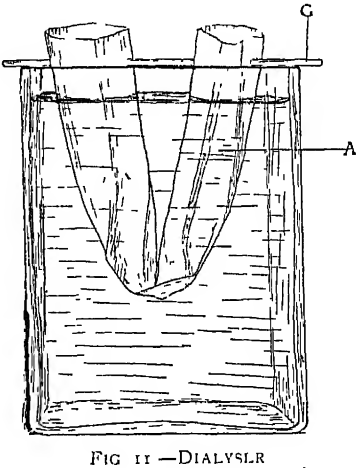

FIG 11 —DIALYSER
A, parchment tube, G, glass rod

paper Determine that the filtrate, *i e* the liquid which passes through the filter paper, gives no blue colour with the iodine solution, in other words, that starch is insoluble in water

17 Boil some commercial starch with water note that it passes into an opalescent, thin, jelly-like condition, but does not dissolve Dilute some of this starch-containing liquid with water and pour it into a parchment shell or tube of parchment paper (Appendix B), bent in the form of a **U**, and supported in a beaker of water by means of a glass rod passing through the upper part of the limbs of the **U** (Fig 11), leave it for twenty-four hours If

starch is a diffusible substance it will pass through parchment paper into the water in the beaker Prove the iodine test that starch is not diffusible

18 Add a little starch—as much as will go on end of a knife blade—to about a half-pint of water beaker, stir well, and boil add by means of a glass two or three drops of a mineral acid, *e g* hydrochloric acid, boil, and at hourly or convenient intervals test liquid for starch thus —by means of a glass rod, distribute drops of the liquid on a porcelain saucer, dip another glass rod into the iodine solution, and mix drops latter with those on the saucer Observe that the reaction becomes fainter as time goes on, and finally Boiled with small quantities of mineral acid, starch decomposed Keep the solution in a clean bottle (I in Exp 25) It is important to find out to what substance or substances the starch has given rise We may hint with respect to this in the course of the following experiments which we perform in order to find out if is generally present in seeds, and if it is widely distributed in other parts of plants

19 Apply the iodine test to the cut and moistened surfaces or to thin slices of the following seeds nut, date, maize, turnip, almond, horse-chestnut, rape, castor-oil plant, and others which can be spared the seed-collection Dissect out the embryos of germinated barley or wheat grains, put them for about an hour into a solution consisting of equal parts saturated chloral hydrate and potassium-iodide (Appendix V) Note that the embryos give a beautiful starch-reaction

20 Cut thin slices of unripe and ripe apples or and compare them as to starch content Test thin of the stems and roots of various flowering plants starch Find out whether starch is present in leaves, *e g* of clover, lime, lily, American water (Elodea canadensis), snowdrop, iris, and other plants this purpose, proceed as follows throw the leaves, should be thin, into boiling water for a minute o Take them out and put them into a wide-mouthed bottle containing methylated spirits stopper or

the bottle, and expose it to sunlight after a day or two, remove the colourless and brittle leaves carefully from the alcohol, wash them in water, and pour over them chloral hydrate, iodine solution as used in the previous experiment Record which leaves contain starch, and which do not Test similarly pieces of fern fronds, moss leaves, the green threads of any algæ which may be found growing in ditches, and pieces of mushroom or of toadstools

When ripe and unripe fruits, apple, etc , were tested for starch, it was noticed that the unripe fruit contained much starch and the ripe fruit far less or even none On the other hand, the ripe fruit is sweet, and the unripe fruit is not It therefore appears likely that the sweetness of the ripe fruit is due to the conversion of starch into sugar This is rendered the more probable in that both starch and sugar consist of the same three elements, viz Carbon (C), Oxygen (O), and Hydrogen (H), and have this further in common, that the proportion of hydrogen to oxygen in their respective molecules is as 2 1 (just as it is in water, the chemical formula of which is H_2O) Bodies having this constitution are classed in the chemical group of the carbohydrates The differences and similarities of the constitution of the molecules of starch and of a sugar may be seen if we write down their respective formulæ

Starch, $(C_6H_{10}O_5)_x$ Sugar (grape sugar), $C_6H_{12}O_6$

The x outside the bracket in the starch formula means that a starch molecule has not 6 carbon, 10 hydrogen, and 5 oxygen atoms, but some multiple of these numbers, *e g* x may equal 100 or more (its exact value is not certain), and assuming that it is 100, the composition of the starch molecule is $C_{600}H_{1000}O_{500}$ If we neglect this complication of the bigness of the starch molecule, and write it $C_6H_{10}O_5$, then it is evident that it only differs from the grape sugar (glucose) molecule by H_2O, in other words, if we could add a molecule of water to one of grape sugar we could represent the conversion of starch into grape sugar thus $C_6H_{10}O_5 + H_2O = C_6H_{12}O_6$ When water is induced to combine with such a body as starch, the change undergone by that body is described as one of hydrolysis These considerations with respect to

the chemical constitutions of starch and sugar s there is no inherent improbability in the view th when it disappears from the ripening fruit, m because it has been converted into sugar

Inasmuch as sugars are widely distributed i and evidently play a part in plant- as well as i nutrition, we must consider their properties W mine that they are soluble, using grape sugar and cane sugar (sucrose) for the experimen also require a ready test for the identification important class of substances The test we e based on the fact that some sugars have the taking oxygen from certain substances, and hence ing these substances to a less oxidised conditi example, such reducing sugars, under suitable co take oxygen from cupric oxide (CuO), reduci cuprous oxide (Cu_2O), thus

$$4CuO = 2Cu_2O + O_2,$$

and inasmuch as cuprous oxide is an insoluble, y substance, we are able to see if it is produced whe tion of sugar is added to one containing cupr Thus, we have a basis for a test for reducing sugar test we apply as follows

21 Pour the liquid to be tested into a test beaker add an excess of potash and then a two of a solution of copper sulphate The prec copper hydroxide $Cu(OH)_2$, which is formed interaction of copper sulphate and potash is dis the excess of potash Boil if a reducing sugar is a yellow-red precipitate of cuprous oxide is f Dissolve grape sugar (which is readily obtainable merce) in water and apply the above test Repe cane sugar observe that grape sugar is a redu cane sugar a non-reducing sugar

22 Pour another portion of the solution of ca into a beaker and add a drop of hydrochloric a for some time, and apply the potash and copper test, observe that a well-marked precipitate is It is evident from the experiment that cane when boiled with a trace of mineral acid, yields a

sugar The process whereby a non-reducing is converted into a reducing sugar is called inversion In the case of cane sugar, the chemical change may be expressed thus

$$C_{12}H_{22}O_{11}+H_2O=2C_6H_{12}O_6$$

The change is one of hydrolysis, that is, one in which water is caused to combine with the original body, in this case cane sugar Instead of using potash and copper sulphate separately in testing for reducing sugars, a ready-made solution called Fehling's solution which produces the same result (Appendix A), may be employed"

23 Test by means of potash and copper sulphate or Fehling's solution the following plant tissues or extracts therefrom ripe and unripe apple, beet, carrot, onion

24 Crush with water in a mortar grains of barley which have been soaked in water for one or two hours filter the extract, label it Extract A Now crush grains of barley which, germinated in a germinator, are showing leaves an inch or two long, prepare a watery extract label it Extract B Test samples of A and B for sugar If neither gives a distinct reaction, concentrate A and B each to a small bulk by heating them in porcelain dishes over a bunsen flame or water bath and then repeat the sugar test It will be found that the extract of the soaked ungerminated grains contains no sugar (or at most a trace) whereas the extract of the germinated grains contains a considerable amount Prove that the sugar is contained in the endosperm It looks certain from these results, and also from those obtained by testing ripe and unripe fruits (apple, etc), that the starch contained in the ungerminated barley and in the unripe fruit becomes converted during germination and during ripening into sugar We have a means at hand of demonstrating that starch *does* give rise very readily to sugar

25 Take the liquid obtained by boiling starch with water and a mineral acid (Exp 18) Test a sample in a test tube for sugar If no marked reaction is obtained concentrate the remainder of the liquid to a small bulk and repeat the sugar test Learning thus that boiling with a

trace of mineral acid suffices to hydrolyse starch to sugar we shall be the more ready to believe that the sugar which appears in ripening fruit or germinating barley is produced by the hydrolysis of starch Presently we shall have to determine what agent in the tissues of the plant is responsible, like the mineral acid of Exp 18, for this conversion of starch to sugar, and of what significance to the seedling is this conversion When we do this we shall require to know the various properties which distinguish sugars from starch One such property, that of solubility in water, is well known

26 Another, that of diffusibility through a parchment membrane, is no less important, and must be demonstrated by the use of the dialyser (Exp 17) Some hours after the sugar solution has been placed in the parchment tube, the liquid contained in the vessel in which the tube hangs is tested for sugar either directly or after concentration to a small bulk The result of the experiment proves that a solution of sugar separated from water by a parchment membrane passes across the membrane into the water This passage is called osmosis, and substances possessing this property are called osmotic substances (see Chapter VII) Let us now refer to our list of seeds tested for starch (Exp 19), and note those from which starch was found to be absent They should include the following —rape castor-oil, almond, date, Brazil nut But these seeds all have either endosperm or fleshy cotyledons, and it is therefore more likely that they contain some form of reserve food-material other than starch, than that they contain no reserve food-material at all A scrutiny of the list shows us that certain of these seeds contain fat or oil, indeed, as we know, they owe their use in commerce to this fact We will select one kind of seed from the above list for examination, *e g* the castor-oil seed (Ricinus communis)

27 Pound a seed in a mortar with a few drops of ether or benzol (Appendix A) (this must not be done near a flame, for ether and benzol are highly inflammable, it is safest to do it out of doors) Pour the ether or benzol extract on a sheet of paper Note that, as the liquid evaporates, it leaves behind a grease spot To the grease spot or to the remains of the crushed seeds, add a drop or

two of osmic acid (Appendix A) Note that the osmic acid produces a black or brown colouration Repeat the test on a drop of salad or linseed oil in a white saucer

28 [b] By means of a dry razor or knife cut thin sections of the endosperm of the castor-oil seed, mount them on a slide, examine them microscopically and run in osmic acid note the brown-black masses of oil

29 Now examine, by means of the above tests, the remains of the endosperm of seedlings of the castor-oil plant in different stages of germination note that, as germination proceeds, the oil disappears from the endosperm From analogy with the occurrence of starch in other seeds and with its behaviour during germination, we conclude that oil and fat are the forms in which some seeds store their reserves of food Like the carbohydrates, fats and oils contain the three elements, carbon, oxygen, and hydrogen, but whereas in the carbohydrate molecule there are twice as many atoms of hydrogen as there are atoms of oxygen, in fats the number of hydrogen atoms per molecule is more than twice the number of oxygen atoms For a fuller description of the chemical and physical properties of fats, and also of sugars, the student should consult a text-book of Organic Chemistry (Bibliography, 10, 11)

Among the seeds which were germinated in the course of experiment (Exp 19), and tested for starch (Exp 26), was the date—the seed of the palm, Phœnix dactylifera The seed itself is remarkable It germinates very slowly, the endosperm is flinty hard, and the embryo, placed about the middle of the length of the seed on the side opposite the groove, is extremely small, and shows, in the ungerminated condition, no distinction into the usual parts Germination-stages of the date seed should be obtained, and put up in museum jars We are not now, however, concerned with the morphological peculiarities of the seed, but with the nature of the reserve materials contained in its endosperm

30 [t] If a thin section of the endosperm of a soaked date seed is examined in a drop of water under the microscope, it will be found that the walls which chamber up the tissue into a number of compartments are extraordinarily thick

If now a similar section is made through the soft e
sperm of a date seed which has been germinating for
months it will be observed that the walls, so thick i
ungerminated seed, have become thin It might be
posed that this was merely a symptom of decay, but
equally open to us to infer that the disappearance o
substance of the walls is evidence that this substance
sists of reserve food-material which serves to nourish
seedling This substance does not give the iodine rea
for starch, but if a thin section of endosperm is first tre
with strong sulphuric acid and then with iodine solu
(Appendix A), a blue colour, like that given by starc
produced This substance of the walls, insoluble in w
and giving a blue colour with sulphuric acid and iodi
called reserve-cellulose It may be found not only in
seeds of palms, but in others such as lupine and Ori
galum, seeds of which plants, both ungerminated
germinated, should be examined

31 [1] If the sulphuric acid and iodine test is applie
sections through the soft parts of plants free from starc
even to small pieces of plant tissues, e g grape or app
blue colour, like that shown by the date endosperm
produced, and if sections are treated in this way
examined microscopically, it is found that the w
which chamber up the tissue into compartments consi
cellulose substances Though the cellulose of the
walls of plant tissues gives the same sulphuric acid
iodine reaction as the reserve-cellulose of date and lu
seeds, it is not identical with this latter substance
chief difference between ordinary cellulose and rese
cellulose consists in this, that the former under
chemical change less readily than the latter Indeed
function of the cellulose substances of the walls of ma
tissues is not to serve as reserve food-material, but to
as a scaffolding to the compartments of these tissues

Having made the discovery that the seeds of plants
tain stores of carbohydrate or fatty material which serv
some way or other for the nutrition of the seedlings
might conclude that our task of investigating the funct
of endosperm and cotyledons was at an end But if
remember to apply the principle which we have laid do

and assumed to be true, that the modes of nutrition of plants and animals are fundamentally alike, we shall be struck by the fact that, so far, we have discovered in the seed no reserve food-substance of a kind similar to that which is so characteristic of the eggs of animals. For example, the hen's egg contains substances which have the property of setting to a solid mass (coagulating) when they are heated. We know from experience that these substances are highly nutritious, and since they disappear from the yolk during the hatching of the eggs, we may be fairly certain that they contribute to the formation of the developing chick. We must therefore first consider the nature of these coagulating substances, and then determine whether similar bodies occur in the seeds of plants.

32 We prepare a solution of white of egg by cracking the shell of a fresh egg and letting the white fall into a dish, beating it with five to ten times its volume of water, and filtering. Heat one part of the solution in a test-tube: note that a white coagulum is formed. A similar precipitate is produced by the addition of alcohol to the white of egg solution. By the use of the dialyser (Exp. 17) we demonstrate that the solution made from white of egg does not pass across the membrane, *i.e.* though soluble, it is not diffusible. Apply the following tests to samples of the white of egg solution in test tubes.

33 * *Xanthoproteic reaction*: add a few drops of strong nitric acid: a white precipitate is produced, which becomes yellow on heating: add ammonia cautiously: the colour of the precipitate changes to orange (Appendix A). *Biuret reaction*: add a *trace* of copper sulphate solution, then caustic soda or potash: a violet colouration is produced. By the substitution of ammonia for the soda or potash, a reddish violet colour is obtained (Appendix A). *Millon's reaction*: add Millon's reagent (Appendix A); a white precipitate is formed, which becomes brick-red on boiling.

Iodine reaction: add iodine, a yellow brown colouration is produced: the tint being considerably deeper than when a similar amount of iodine solution is added to pure water.

The group of chemical substances which have the above

properties and give these reactions is called the proteins and the chief protein contained in white of egg is called albumin (Appendix A). If, as we have already reason to believe, the proteins contained in eggs serve as reserve food-material we shall expect to find them also in the bodies of animals

34. That they do occur in the adult body we prove by mincing fresh meat and pounding the fragments in a mortar with water. The extract is then filtered and the filtrate tested as in Exp. 33. We determine also that proteins occur in milk by diluting fresh milk with water and adding *dilute* acetic acid. Filter and test the precipitate for proteins. The curdling of milk is evidently connected with the presence of proteins.

The results of chemical analysis of the proteins show that beside carbon, oxygen, and hydrogen, they contain nitrogen and sulphur, and that some also contain phosphorus.

35. Demonstrate that proteins contain carbon, nitrogen, and sulphur thus: heat chopped, coagulated white of egg in a porcelain dish; note that it becomes dry and subsequently chars—an indication that it contains carbon. Chop finely some pieces of the white of a hard-boiled egg, dry in a desiccator (or better, use dry, powdered albumin instead, see Appendix A), grind in a mortar with soda-lime (Appendix A), transfer to a short tube of hard glass closed at one end. Heat in a bunsen flame, if necessary using the blow-pipe. Note the smell of ammonia; hold a piece of red litmus paper over the open end of the tube, observe that it becomes blue. Since ammonia (NH_3) is produced, albumin must contain nitrogen. A piece of lead acetate paper blackens when held in the fumes escaping from the heated tube, the blackening being due to the formation of lead sulphide (Appendix A), hence proteins contain sulphur. We recollect that a silver spoon left long in an egg becomes black (owing to the formation of sulphide of silver), and we recall the smell—of sulphuretted hydrogen—of a bad egg.

To study further the properties of the proteins is beyond the scope of our present work (Bibliography, 10, 11). We can only say that they may be classified according to

their properties, particularly according as they are soluble in water (albumins), insoluble in water but soluble in dilute solutions of such salts as sodium chloride, magnesium sulphate, etc (globulins), soluble only in strong salt-solutions, insoluble in any of these reagents (*e g* coagulated albumin) One substance with essentially protein-like properties, but with marked peculiarities, must be mentioned, and its reactions noted

36 * Take a small quantity of peptone (which is obtainable in commerce, Appendix A), add water Note that it dissolves Heat note that it does not coagulate Apply the xanthoproteic and Millon's tests for proteins Test a solution of peptone and another of albumin by means of the biuret test Compare the violet reaction of the albumin with the rose-pink reaction of the peptone solution

37 * Demonstrate by means of the dialyser of parchment tube that peptone, unlike proteins, is capable of osmosis In performing this experiment, which will last several days, owing to the fact that the rate of osmosis of peptone is slow, a *trace* of an antiseptic such as thymol or eucalyptus oil (Appendix A) should be added to a strong solution of peptone At daily intervals, withdraw some of the liquid from the outer vessel and test a sample of it for peptone by means of the biuret test If, owing to the dilute ness of the solution, no reaction is obtained, concentrate to a small bulk and repeat the test

We learn from our study of the proteins that they are complex bodies containing the elements Carbon (C), Oxygen (O), Hydrogen (H), Nitrogen (N), Sulphur (S)—some also contain Phosphorus (P)—that they have remarkable properties (of coagulation, etc), that they may occur in the eggs and also in the mature bodies (*e g* the flesh) of animals (Exp 34), and that there is good reason to believe that they serve for the nutrition of animals We have in the next place to enquire whether the seed and the mature plant also contain proteins

38 * Cut thin sections of the tip of a root or stem of any young plant or of the young stamens of a lily or other flower Mount in water on a slide in the usual way Examine by means of the microscope Run in iodine, and note that the contents of the compartments into which these

tissues are chambered give the yellow-brown reaction fo proteins

39 * Repeat Exp 35, using, instead of white of egg c dry albumin, chopped and dried grass, or pea or bea meal Note that these vegetable tissues yield evidence th they contain nitrogen and sulphur Thus from the resul of the last two experiments we infer that proteins a present in plants Confirm this as follows —

40 * Extract pea or bean meal or soaked and pounde wheat grains (1) with water, (2) with a dilute (5 %) solutio of magnesium sulphate filter, and demonstrate by mean of the protein tests applied to the filtered extracts th proteins are contained in the seeds of bean or pea an wheat

41 * Put a little flour in a fine muslin cloth folded form a bag Hold the muslin bag under a tap, and allo water to run on the flour, which should be kneaded a squeezed between the fingers Observe that the starch washed away, leaving a sticky mass of gluten Demo strate that this residue contains proteins (Exp 33)

Hence we conclude that the reserve-materials contained in the seeds of plants are of like nature to those contained in the eggs of animals, and consist not only of carb hydrates (or fatty substances), but also of proteins

42 * In order to determine the condition of, and th place in the seed occupied by, the protein reserve material we cut, preferably by means of a dry razor, section through small pieces of the cotyledons of a bean or pe seed mount on a slide in a drop of iodine solution Observe that, lying among the starch grains (stained blu by the reagent), there are many much smaller grain which show the yellow-brown colour-reaction characteristi of proteins Similarly, cut sections of the dry endosperm of wheat or maize or other grass grains Mount th sections in iodine solution, and note that the protein grains or, as they are sometimes called, aleurone grain are confined to the layer just beneath the seed coa Apply the biuret test to other unstained sections b adding the copper sulphate and potash to the section placed on a glass slide Heat, and, when cool, drain aw the fluid, add a drop of water, put on a cover glass an

examine under the microscope Treat other fresh sections with Millon's reagent and examine with a lens note the red colour of the aleurone grain layer

It is, however, in oily seeds that the protein grains reach their highest development In order to prevent the solution of the water-soluble parts of the aleurone grains, we adopt the precaution of moistening with oil the razor used for cutting sections of the endosperm of such seeds, *e g* castor-oil and Brazil nut Sections obtained from these seeds, mounted in oil (*e g* olive oil) and examined microscopically, show numerous, large, oval, transparent aleurone grains, each with a darker granule (the globoid) at one end If such sections are compared with others cut in water, it will be seen that, in the latter, a part of the contents of the aleurone grains has dissolved, leaving behind a crystal-like body—the crystalloid—which occupies the larger part of the grain Apply to sections cut with a dry razor the various tests for proteins The globoid, to which reference has been made, has been proved to contain various mineral substances, *e g* compounds of calcium, magnesium, and phosphorus, and it has also been shown that these substances disappear from the aleurone grains during germination, passing, as there is reason to believe, to the embryo Hence to our list of reserve food-materials, carbohydrate, fat, and protein must be added mineral substances, though, in most cases, seeds contain reserves of mineral substances in quantities insufficient for the requirements of the seedling

CHAPTER IV

THE changes undergone by the reserve food materials of the seed duri germination the mode of passage of food materials from the place storage (endosperm or cotyledons) to the place of consumption (tl growing embryo)

WE learned in Chapter III that even a very small see contains a certain amount of those substances, starch c oil, etc , which constitute reserve food-materials, and th the larger seeds possess rich stores both of carbohydrate or fatty and of protein (nitrogenous) food-substance accumulated either in the endosperm or in the flesh cotyledons We learned further (Exp 13) that, in th course of germination, as the embryo develops to th seedling, the food-materials disappear from the endosperm or cotyledons We inferred, therefore, that they are trans ported thence to the growing parts of the seedling

This inference receives support from the experiment which we now perform, of germinating large and sma seeds, *e g* broad beans and poppies or "California poppies" (Eschscholtzia californica) in darkness

43 Sow the seeds in small pots containing ordinar soil, and place the pots in a light-proof box (Fig 12 or cupboard The pots must be taken out of the dark bo from time to time, in order that the seedlings may b observed and measured, but they should be replaced im mediately after inspection As the experiment proceeds, w observe that, though the seeds germinate quite well, th seedlings produced in darkness are curious, pale plants, an that, whereas the bean plants live for three, four, or mor weeks, the poppy or Eschscholtzia seedlings live only for limited number of days In other words, as we shoul guess from their appearance, both beans and poppies di

ultimately of starvation, the latter very soon, the former only after a fairly long interval of time—not indeed, as we determine by observation, till the reserve food-materials originally contained in them have disappeared from the cotyledons.

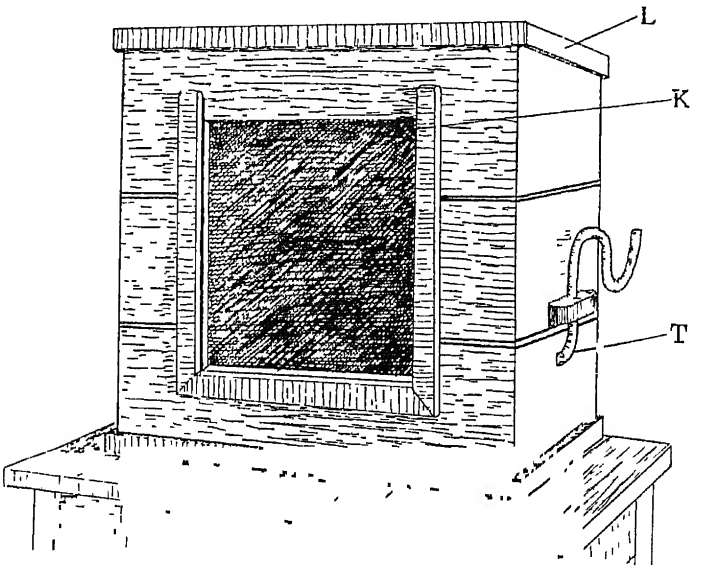

FIG 12.—DARK BOX (See Appendix, p 234)
L, lid, K, shutter, T, aerating tube

We cannot fail to attribute the longer life of the dark-grown bean seedlings to the large stores, and the shorter life of the dark-grown poppy or Eschscholtzia seedlings to the slender stores of food-materials which the seeds contain

But if we recall the conditions in which the reserve food-materials exist in the seed, and the properties of these substances, we find ourselves confronted with a difficulty, namely, that of understanding how these food substances pass from the one place to the other—from the tissues of

the endosperm or cotyledons, to the growing root ar
shoot of the seedling We know that the starch co
sists of solid grains which lie in compartments bounde
by cellulose walls, we know that starch and oil a
insoluble in water, and that much of the protein of th
aleurone grains is also insoluble (Exp 42) Since th
reserves are insoluble, it would appear to follow that the
are irrevocably imprisoned in the tissues of the endosper
or cotyledons Yet we have just obtained evidence (Ex
43) that the reserve-materials are liberated from the tissu
and distributed to the embryo If, however, we state the
apparently contradictory facts in a somewhat modifie
form, we shall see that they are not irreconcilable Th
reserve food-materials of the resting seed consist of sol
granules (starch and protein) or of droplets of oil whic
substances are—except some of the proteins—insoluble
in water, and therefore incapable of traversing th
cellulose walls of the compartments in which they li
In the active, germinating seed, food-materials reach
the embryo and, at the same time, the reserves
endosperm or cotyledons decrease and tend to di
appear Therefore, the active seed must have a mean
of so changing the reserve food-materials that they are
longer compelled to remain imprisoned in the tissues
which they were laid down, but are free to travel then
to the embryo It is evident that, for substances t
pass from the tissues of the endosperm to those of t
embryo, they must be soluble in water and capable
osmosis If we accept this reconciliation of our fact
we proceed to ask, into what soluble and diffusib
substances may the reserves of the seed be changed? Fo
instance, into what soluble, diffusible substance may star
be transformed? The answer is suggested already by t
results of Exps 18 and 25, which show that starch, boil
with traces of mineral acids, becomes converted in
sugar But if this hydrolysis of starch to sugar actua
occurs in the endosperm, it certainly is not due to t
agents, heat and traces of mineral acids, employed in e
experiment Granting, therefore, that our reasoning h
been sound, we are driven to conclude that there must
present in the germinating seed some special agent whic

like the mineral acid, is capable of effecting the hydrolysis of starch to sugar, but which, unlike the trace of mineral acid, is capable of effecting this change with rapidity at ordinary temperatures Thus we arrive at a point in our argument at which we formulate a definite hypothesis, and put that hypothesis to the test of experiment We state our hypothesis thus the starch contained in the endosperm of resting seeds is converted during germination, by some unknown agent, into sugar To test our hypothesis we ask (1) does this transformation actually take place? (2) if so, by what agent is it effected?

44 To obtain a positive answer to the first question we have only to repeat Exp 24, viz pound up in a mortar about $\frac{1}{4}$ of a pound of the grains of sprouting barley or wheat, add a little water, and continue the pounding filter, and test a portion of the filtrate for sugar (see Exp 21)

To obtain an answer to the second question, we take the remainder of the filtered extract just obtained, put it in a large beaker or bottle, add gradually, several times its volume of methylated spirit till a heavy precipitate is produced Allow the liquid to stand for an hour or more till the precipitate has settled Pour off the bulk of the liquid, taking care not to stir the precipitate Transfer what remains of the liquid, together with the precipitate, to a filter As soon as the liquid has drained away, take the filter paper from the filter funnel, open it out, spread it on a plate, scrape off the precipitate by means of a wooden spatula, and transfer it to a small, wide-mouthed, stoppered bottle Add about 20 c c of distilled water, shake thoroughly, and filter, if necessary Put the solution thus obtained into a clean bottle, add a *trace* of an antiseptic, *e g* thymol or eucalyptus oil, and label it Before investigating the action of this extract on starch, it will be necessary to test a sample of it for sugar For this purpose take out about 1 c c, dilute it with 5 c c of water, and apply the sugar-test If only a slight sugar reaction is obtained, it may be disregarded, but, if the test proves that sugar is present in considerable quantities, the remainder of the extract must be treated again with an excess of alcohol (methylated spirit), the

liquid filtered, and the precipitate redissolved in wa the same way as before

45 Put a very little, pure starch powder in a be add water boil thoroughly dilute the boiled liquid it is almost clear, take three test tubes labelled A, To A add some of the starch liquid only, to B starch and about 2 or 3 c c of the extract prepared in Exp C add water and 2 or 3 c c of the same extract I the tubes in a warm place at any temperature bet 20°-30° C At hourly or convenient intervals, tes liquids in A, B, C, for starch, using the method desc in Exp 18 Determine that, whereas the blue s reaction of the liquid in A remains, the reaction giv B gradually becomes fainter C, which serves the a unnecessary purpose of demonstrating that the alc extract itself contains no starch, gives no starch reac When B gives only a faint starch reaction, concentrat heating in porcelain dishes, each of the liquids in A, to a small bulk, and test them for sugar The fact th gives a well-marked sugar reaction provides us wit proof that our barley or wheat extract contains the stance for which we are seeking, viz an agent whic moderate temperatures such as those at which germinate, converts starch into sugar The experi proves, moreover, that this agent is extremely potent the amount contained in the 2 or 3 c c added to B but little

46 Whilst the preceding experiment is going on, pare an extract from *unsprouted* barley or wheat whic been soaked just long enough to become soft Ascer by similar experiments to those made in the prev experiment, that the amount of the starch-hydroly agent present in the ungerminated grains is less th the sprouted grains

The starch-hydrolysing substance which we have tracted from germinating barley is known as diastase, may be obtained in commerce For subsequent ex ments, commercial diastase may be used

It will be interesting to observe diastase at work o individual starch grains For this, use commercial dia (Appendix A) (or our own extract, Exp 44)

47. Prepare sections or a fair quantity of scrapi wheat endosperm take two watch glasses A and B two other watch-glasses to serve as covers To A some of the scrapings or sections and a little di solution, to B, add water only Cover the watch-g to check evaporation, and put them in a mode warm place (temperature 20°-35° C) After several l mount the sections or the isolated grains of the scrapi

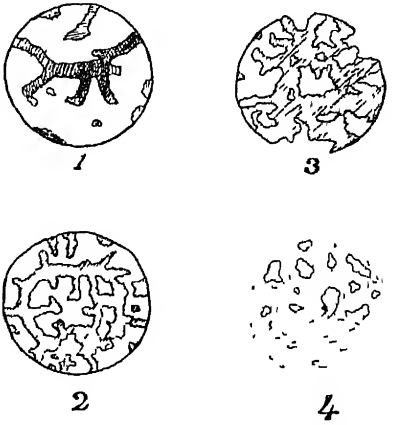

FIG. 13.—STARCH GRAINS OF GERMINATING BARLEY, TO ILLUS THE ACTION OF DIASTASE

1, 2, 3, 4 Successive stages of corrosion of the grains Cf Fig 10 (After Strasburger, *Textbook of Bota*

a drop of water, examine them microscopically, and ob that the grains which have been acted on by the dia begin to show signs of change they swell, radial fis appear, each grain comes to have a corroded appear and subsequently nothing remains of it but a pale or ghost (Fig 13) Apply the iodine test to the grai various stages of dissolution (Avoid in this experi the use of starch grains, such as those of the bean, v show radial fissures in their natural condition)

We have thus obtained the experimental proof o

truth of our hypothesis, and may now, therefore as a fact that the germinating grains of barley contain an agent which converts starch into su using other seeds, e.g. beans, peas, etc., we p diastase, the agent of this change, occurs ger starchy seeds. A visit to a maltster's works w us to see in the malting of barley, as carried preliminary to brewing, a large-scale illustrati action of diastase. In the preparation of malt, spread out on the floor of a room which is kept w grain is moistened thoroughly, and allowed to g When germination has proceeded to a certain ex temperature of the room is raised gradually to at which the barley is killed. The action of the is allowed to continue till most of the starch converted into sugar, which serves, in the su operation of brewing (see p. 58), for the prod alcohol.

Having proved that, during the germination o seeds, insoluble starch is converted into soluble fusible sugar, we conclude that it is in the la that carbohydrates migrate from endosperm or c to the several parts of the growing embryo.

We now proceed to learn something more of perties of diastase and determine first that it is c hydrolysing, not only the starch of seeds, but which occurs in mature plants.

48.* This we do by treating with diastase, as described in Exp. 17, sections or scrapings of th growing potato tubers. After a certain time, t grains show corrosion figures similar to those w have already seen in germinating seeds.

We note, moreover, that diastase has no solve on the cellulose of the cell walls which are to be se sections. The starch grains contained in leaves shown, by means of sections of leaves treated with to disappear under the action of this agent. Thus the conclusion that whenever the plant needs to u of starch, it first hydrolyses it to sugar by i diastase. We may say that starch is the reserve, o form, and sugar the translocation (travelling) form

by the carbohydrate material of a great number of plants Before such a carbohydrate as starch—and the same applies to reserve-cellulose (Exp 30)—is used as food-material by the plant it is converted into sugar Hence we recognise that diastase must be as widely distributed in plant-tissues as starch itself

Now we have used more than once what we know to occur in animals as a starting point for our enquiries into the processes which take place in plants We will here reverse the procedure and ask has what we have learned concerning diastase and its action on starch any bearing on animal physiology? We know that starch enters very largely into the composition of animal food, and that the food which we swallow does not pass directly into the body, but into a tube—the alimentary canal—the parts of which are œsophagus, stomach, and intestines We know further, that the food undergoes digestion, and that not till it has been digested does it pass through the wall of the alimentary canal into the blood We suspect, therefore, that a knowledge of the action of diastase on starch may help us to an understanding of the significance of the process of digestion which food-substances, such as starch, undergo in the alimentary canal of animals Just as insoluble starch cannot pass across the walls of the endosperm tissue, so it cannot pass through the complex wall of the stomach or small intestine, and just as soluble, diffusible sugar passes across the cell-walls of the plant, so it may pass across the walls of the absorptive part of the alimentary canal and of the blood vessels, etc, and thus, reaching the blood stream, be distributed throughout the body of the animal It will be interesting, therefore, to discover whether diastase, which is present so generally in plants, occurs also in animals

49 We do this in the following ways Prepare a solution of saliva By chewing a piece of indiarubber or by inhaling a little vapour of glacial acetic acid, a flow of saliva is induced collect the saliva in a small beaker or porcelain dish: add an equal volume of water stir thoroughly, and filter Using the method described in Exp 45 demonstrate the diastatic action of saliva, *i e* its power to hydrolyse starch to sugar A sample of commercial, salivary dias-

tase, known as ptyalin (Appendix A), should be obtai and its starch-hydrolysing properties tested

Food is retained in the mouth for such a short time t much of the starchy material which it contains escapes action of the diastase (ptyalin) of saliva, but on reach the small intestine, the partially digested food is acted by pancreatic juice, which also contains a diastase By action of the pancreatic diastase, the conversion of sta into sugar, which was begun in the mouth, is completed

The diastase contained in pancreatic juice is present i in the extract of the pancreas, known commercially liquor pancreatici (Appendix A), and the hydrolys effect of this liquid on starch may be demonstrated by method of Exp 45

The above experiments throw a clear light on what meant by digestion As far as starch is concerned, dig tion means the conversion of this substance, by me of the special agent diastase, into soluble, diffusi sugar They also provide yet another illustration of fundamental agreement between the nutritive processes plants and animals Both use starch as a food-mater and both prepare this substance for distribution throu the tissues in precisely the same way By similar metho of procedure, to some of which reference will be ma subsequently, it may be shown that the digestion of ot substances, such as fats and proteins, means, in l manner, the conversion of the fat or protein, each, means of a special agent, into soluble and diffusible su stances Each of these agents is a specialist, th diastase acts on starch and starch only We want general name to include these specialists in chemi change They used to be called unorganised fermen but are now known as *enzymes* We may form a rou and unfinished picture of the mode of action of the enzyi diastase, on the starch molecule thus imagine it holdi out one hand to a molecule of water and the other to c pan of the many $C_6H_{10}O_5$ groups which make up the star molecule (see p 33) Swinging its two imaginary hand diastase brings the two $C_6H_{10}O_5$ molecules and the H molecule together, unites them as $C_{12}H_{22}O_{11}$ (malt suga and, having done so, is free to lay hold again of a wa

molecule and another pair of the $C_6H_{10}O_5$ groups, and to treat them in a similar way Thus we can picture diastase effecting the piecemeal disintegration of the starch molecule by hydrolysing its constituent groups In this sense we may describe the action of diastase on starch as clastic (breaking down) and hydrolytic (water-adding) It is by similar clastic and hydrolytic processes that other enzymes act

To return to the study of the properties of enzymes as illustrated by diastase as we have already remarked, a little of the enzyme goes a long way in producing its specific change Nor, having regard to our description of the mode of action of diastase, is this altogether incomprehensible for, according to that description, the enzyme only plays the part of an intermediary, presenting a molecule of water and two $C_6H_{10}O_5$ molecules to one another The presentation effected, the enzyme is free to bring about another, similar union between water and two more $C_6H_{10}O_5$ molecules In Exp 45 we found that even though the diastase was allowed to act on starch for several days, not all the latter was converted into sugar That this was due not to the exhaustion of the enzyme but to the conditions of the experiment we demonstrate by repeating the experiment thus

50 Prepare solutions of diastase and of starch (as in Exps 44 and 45) Add a known amount of the starch liquor to a large test tube or beaker (A), and a corresponding amount to a parchment tube or diffusion shell (B), as described in Exp 17 Add a measured quantity of the diastase solution to A and an equal quantity to B Stand A and B in water kept at a moderate and as uniform a temperature as possible After some hours, and then at convenient intervals, test A and B for starch At the end of 12-24 hours replace the water in which the parchment tube dips by fresh water Determine that, whereas A continues to give some colouration with iodine, B ceases, after a time, to give the iodine reaction This means that, though some starch remains in the test-tube, all traces of it disappear from the parchment tube Since the only difference between A and B is that, whilst the sugar formed by the action of the diastase on starch accumulates in A,

it passes by osmosis from B into the water surrounding the parchment tube, we conclude that the accumulation of the products of enzyme activity tends to bring the action of that enzyme to a standstill In other words, enzyme action is inhibited by the products of that action

By a suitable and easily planned series of experiments we may determine that diastase is very susceptible with respect to its starch-hydrolysing powers to external conditions Thus diastase acts slowly at a low temperature more rapidly as the temperature increases to about 60° C and slower again at yet higher temperatures. Heated to about 85° C it is 'killed,' *i e* its hydrolysing powers are destroyed

Again, diastase—like other enzymes—may be shown to be very susceptible to other conditions, *e g* acidity or alkalinity of the medium in which it acts

We will now summarise what we have learned concerning the properties and mode of action of the enzyme, diastase Diastase is a soluble, indiffusible substance (see Exp 4-) occurring in both plants and animals, among which it is widely distributed Whenever starch is undergoing digestion, diastase is present as the active agent of that change Starch is a reserve form of carbohydrate food-material It is insoluble, and hence, though excellent for storage purposes, is immobile and unusable as food Sugars are plastic forms of carbohydrate They are soluble and diffusible, and hence are mobile and usable as food The rôle of diastase is to convert the reserve carbohydrate (starch) into plastic carbohydrates (sugars) Its mode of action is hydrolytic and elastic A specialist among chemical agents, it acts exclusively on starch On that substance its action is potent given suitable conditions of temperature, slight alkalinity of medium, removal of the product of its activity a very little diastase suffices to effect the conversion of large quantities of starch to sugar. The action of diastase on the starch contained in starchy seeds begins as soon as the latter are placed under conditions which admit of germination For further information on the subject of diastase, see Bibliography, 10, 11

Our study of the action of diastase on starch has served to give us a clear and precise idea of what goes

on in the course of the digestion of food by an animal We have seen that both saliva and pancreatic juice contain diastase, and that both, in consequence, convert starch to sugar If we extend our ideas gained from the mode of action of diastase on starch to digestion in general, we are led to conclude that digestion in animals means—apart from any mechanical action—the production, by the action of special enzymes, of soluble, diffusible, plastic substances, from insoluble, indiffusible materials supplied to the animal in the food Similarly, applying the same conclusion to plants, we predict that just as a diastatic enzyme converts insoluble starch into soluble, diffusible sugar, so, in oily seeds, a specific enzyme effects the conversion of the oil into soluble plastic substances, and in seeds containing protein (aleurone) grains, other enzymes effect similar changes in the indiffusible and, for the most part, insoluble proteins Not only shall we expect to find these enzymes in the germinating seeds, but also in any parts of the plants which contain reserves of food-materials liable to be drawn upon for the purpose of nutrition This hypothesis we proceed to put to the touch of experiment

51 * Prepare solutions of commercial diastase and of liquor pancreatici (Appendix A) Cut out small cubes of the white of a hard-boiled egg which, as we know, contains insoluble, coagulated proteins Place a cube in each of two test tubes, and also in a diffusion shell or parchment tube standing in water, add diastase solution to one test tube and diluted liquor pancreatici to the other test tube, and also to the diffusion shell, add a drop of thymol to each of the tubes to prevent the growth of bacteria, and keep them at a temperature of 35°-40° C We note after some hours that, whereas the white of egg to which diastase has been added undergoes no change, that exposed to the action of liquor pancreatici becomes irregular in outline, smaller and translucent Noting these changes, we recall the fact already discovered, that protein-like substances (peptones) exist which are both soluble and diffusible (see p 41, Chapter III) Now, from our study of diastase, we should not be unprepared to find that if pancreatic juice digests proteins, soluble and diffusible bodies result from this digestion.

52 Therefore, after the pancreatic juice has acte the white of egg for some time take a sample of liquid and test it for peptones by the biuret test rose colour which results from the application of test indicates that the pancreatic juice has effected conversion of insoluble, indiffusible, coagulated albu into soluble, diffusible peptone After 12-24 hours, a the peptone test to a sample of the liquid in the vessel which the diffusion shell (or parchment tube) dips I peptone reaction is produced, concentrate half of liquid to a small bulk and repeat the test Note t though the liquid is shown to contain the protein-like b peptone, no coagulation occurred during the operatio boiling down the liquid to a small bulk, for pepto unlike the soluble proteins, are not coagulated by heat may be necessary to allow the experiment to continue s days before peptones are recognisable in the water of outer vessel

53 Start another digestion experiment with white egg, or curdled milk, and liquor pancreatici, using, h ever, a *very small quantity* of the substance to be diges Before all the solid white of egg or curd of milk has appeared from the test tube, test for peptone. T replace the tube and test again at intervals of six or n hours It will be found that, as the action of the pancre juice continues, the peptone reaction gets fainter, and fin fails Peptones, therefore, are not the final products of digestion of proteins by pancreatic juice By appropr experiments it may be shown that the peptones give pl to simpler nitrogen-containing bodies, among which r be mentioned leucin, tyrosin, and asparagin (Bibliograp 11) It would take up too much time to investigate th final products of the pancreatic digestion of proteins, we may state that they have been shown to belong to cert groups of nitrogen-containing, organic substances kno as the amino-acids and their derivatives (Bibliograp 11)

The main facts which we have learned from the stu of the pancreatic digestion of proteins are as follow During digestion, soluble and diffusible substances are p duced The digestion takes place in two stages, in the fi

CHAPTER V

THE meaning of the term Nutrition the use which the plant makes food substances The germinating seed considered as a machi The source of the power which drives the machine and the conditic under which it works

WE concluded from the results of our experiments Chapter IV that the reserve materials of the seed a rendered soluble and diffusible by the action of enzyme and that the plastic food-substances thus produced ser to nourish the seedling We have now to discover wh is meant by the nourishment of the seedling in oth words, we have to find out to what uses the plant pu plastic food-materials

It would be possible to begin this work by experimenti with seedlings, but our task will be simplified if we choos not one of the more complex, higher plants, but one of tl simpler, lower plants

Of the lower plants which may be used for a study nutrition, the most convenient is that used by brewers set up alcoholic fermentation in sugar The plant question is known as yeast (Saccharomyces cerevisiæ), a may be obtained in commerce

55 Having purchased a small quantity of active yeas we prepare a nutrient solution, *e g* Pasteur's nutrie solution (Appendix A), in which it is known that yea grows well Half fill a small flask with the solution, bc it, remove the flask from the bunsen flame, plug tl neck with a wad of cotton wool, and set it aside to coc Pass a needle mounted in a pen-holder once or twi through the flame of a bunsen burner in order to steril

its point Allow it to cool, take up a little of the yeast on the point of the needle and transfer it to the cooled liquid in the flask Plug the neck of the flask again with fresh cotton wool, label it appropriately, and stand it in a warm place (25°-30° C) After some days, note that the contents of the flask have become turbid By mounting a drop of the liquid on a slide and examining it under the high power of the microscope, it will be seen that the turbidity is due to the presence of innumerable spherical or oval bodies, which, if the magnification is sufficiently great, present the appearance shown in Fig 14

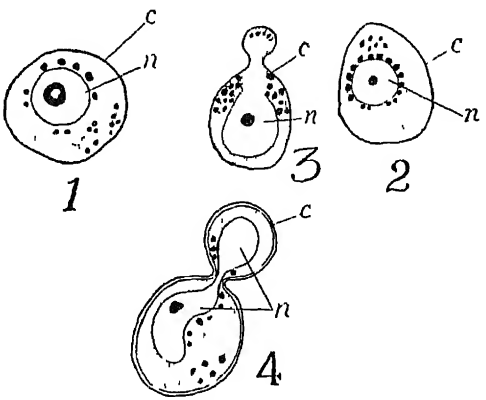

FIG 14 —YEAST CELLS

1, 2 Living yeast cells, from a sample of brewers yeast Very highly magnified 3, 4 Living yeast cells, growing actively (budding) in Pasteur's nutrient solution *c*, cell wall, *n*, nucleus (After Wager, 1910)

We note that these oval bodies are of different sizes, and that some of them are in process of division or of budding off cells like themselves (Fig 14) Hence they are evidently alive Each oval or spherical particle which constitutes a complete yeast plant is called a cell or protoplast, and since a single protoplast is capable of nourishing itself, growing, dividing, and, in fact, leading an independent existence, we say that yeast is a unicellular plant

56 If a drop of potassium-iodide iodine solution is r
under the cover glass, the granules become of a ye
brown colour Similarly, if some of the turbid liqu
filtered through glass wool—or if some of the ori
yeast is taken and pounded up with clean silver sand
mortar, it may be shown, e g by Millon's reagent (
33), that the pounded contents of the yeast cells co
proteins We thus confirm the result of the iodine
applied to the individual yeast cells We conclude that
cell which, since it feeds, grows and divides, is alive,
tains substances which, after being killed, give the
actions characteristic of proteins Since the amount of
borne on the needle point has sufficed to produce
relatively enormous quantity now present in the flas
is clear that there has been a very considerable augme
tion of the amount of proteins, etc , present in the ori
cells placed in the flask Therefore, the living yeast
supplied with appropriate nutrient materials, which inc
sugar and also traces of nitrogen-containing bodies, b
up proteins and incorporates them into its living subst
In this process of incorporation, both carbohydrate
nitrogen-containing materials are employed As a r
of this process, the amount of living substance is increa
Of the chemical constitution of living substance we k
little or nothing We know that when it is killed it g
invariably protein reactions, and hence infer that prot
are among its essential constituents We call the li
substance protoplasm We conclude, therefore, that
most important use to which the yeast plant puts
materials which it derives from the nutrient solutio
the manufacture of fresh living substance

Applying these conclusions to the seedlings of flowe
plants, we may conclude that one use of the plastic fo
substances is to supply the protoplasm of the seedling
materials for the construction of new protoplasm I
this process of manufacture goes on in the tissues of
seedling we already have evidence We know
during germination the embryo increases enormo
in size We find also, from a microscopic ex
nation of sections through the young root and sh
of seedlings, that their tissues are made up of mi

masses of substance, giving, like the yeast cell, the yellow, iodine reaction The number of these masses is far greater in the germinating seedling than in the embryo contained in the seed Therefore, we conclude that, just as the yeast plant consists of protoplasts which undergo division, so the tissues of the seedling consist of protoplasts which undergo division The only essential point of difference lies in this, that, whereas the yeast cells, after division, separate from one another and constitute each a unicellular plant, the protoplasts constituting the tissues of the seedling do not separate, but remain connected with one another In other words, the seedling is a multicellular organism and not a unicellular organism like yeast

When we examined the sections of plant-tissues (Exp 31[1]), we found that the tissues are divided by walls of cellulose into small compartments, and we recognise now that the protoplasm which gave the yellow-brown colouration with potassium-iodide iodine solution is the living thing—the protoplast, and that the cellulose walls are but a scaffolding or supporting framework to the protoplasts Since, as the seedling grows, the number of cells increases, there must be, beside the increase of living protoplasm, an increase of the cellulose substances which form the walls around each protoplast These walls are formed by and from the protoplasm Part of the latter, undergoing breaking-down processes, produces cellulose, which is deposited either between two cells which have just divided, or on the already formed walls of young cells Thus, the protoplasm makes from the plastic food-substances, not only more or less permanent additions to its own substance, but also uses up some of its substance in the production of cell-walls Such manufacture by the protoplasm of the various substances needed by the organism for special purposes is called secretion We may say that the cell-wall substance is secreted by the protoplasm, that diastase or any other enzyme, such as we know to be produced by plants or animals, is secreted by the protoplasm, and so on The plastic food-substances supplied by the endosperm or cotyledons to the growing seedling provide materials which serve for the increase of the protoplasm of the seedling

But not all this increase is permanent, for some of protoplasm is devoted to the secretion of special substan such as cellulose, enzymes, etc Hence some of the stituent molecules of the plastic food-substances migra from the endosperm become, in the seedling, integral p of protoplasm, and some, having been for a time stituents of the protoplasm, serve for the formation of various secretions Moreover, if the rate of passag sugar from endosperm to seedling is faster than the rat which the sugar is being used by the seedling, the sur may be reconverted into starch and stored temporaril the seedling in that form (see Exp 19)

We thus obtain a definite idea of what is meant nutrition This process involves the incorporation of tain of the constituents of plastic food-substances with protoplasm, which becomes thereby increased in quant it means also the provision of materials not only for permanent increase, but also for the manufacture, by living protoplasm, of the many various substances wh play a part in its life

Now, if this were a complete account of the fate of plastic food-materials which the seedling derives from reserve food-materials, it would mean only that elements contained in the reserve materials pass to seedling, and, undergoing recombinations, become parts the protoplasm, of the cell-wall, of enzymes, and of ot secretions If this were the case, there would be, a were, merely a transmigration of matter from the en sperm or cotyledons to the seedling, and the dry wei of a seedling which has access to the reserve-materials o for its supplies of food, would neither increase, decrease, as germination proceeded Whether this is case or not we can put to the proof of experiment

The problem which we have to solve is as follows a seed is germinated under such conditions that it can obtain supplies of food-materials except from its reser in cotyledons or endosperm, does the dry weight of seedling remain constant, or is there an increase or decre in dry weight?

We know that the germinating seedling takes up wat and, therefore, its undoubted increase in weight might

due merely to the water which it absorbs We know also that the cotyledons, e g of the bean, shrivel as they lose their reserves of starch, etc Is the loss of dry weight by the cotyledons exactly balanced by the gain in dry weight by the rest of the seedling?

This is a matter of such importance that though the experiment is tedious, and requires fairly accurate weighing by means of a chemical balance (Appendix B), all students should attempt it

To carry out the experiment we proceed as follows

57 Pick out about 60 seeds of kidney bean (Phaseolus vulgaris) or other plant with large, epigean cotyledons Soak the seeds for twenty-four hours in tepid water Select 50 seeds of approximately similar size, divide them into two lots of 20 each, reserving the other 10 Weigh the two lots of 20 Plant one lot in pots in moss or coco-fibre, and plant also the 10 reserved seeds in case any of the 20 fail Put the pots in a dark room or box, being careful that no light falls upon them Give water when necessary

Squeeze out each seed of the other lot of 20 from its seed-coat, pound the seeds thoroughly in a mortar, and, when they are thoroughly crushed, transfer them to a weighed porcelain dish and dry in a drying oven at 100° C After a day, take the dish from the oven, place it in a desiccator to cool, weigh, replace in the oven for twenty-four hours, then remove, cool, and weigh as before We thus obtain the dry weight of ungerminated seeds (less the weight of the seed-coats, which does not concern us) After a fortnight, when the dark-grown seedlings have grown to a considerable size, turn them out of their pots, remove, by washing, all pieces of moss, etc , from their roots, select 20 seedlings, weigh, chop, and then grind them in a mortar and determine their dry weight

The difference between the fresh weight and dry weight of the seedlings gives a measure of the amount of water taken up in the course of germination A comparison of the dry weight of the 20 germinated seeds with the 20 similar, ungerminated seeds, shows that in the course of germination the dry weight of the seedlings has decreased

We prove, thus, that during the work of germination

there is an actual loss of material by the plant. Not only is food-material passed from cotyledon to seedling, but also the plant, if prevented from getting food-material from other sources, loses some of the material which it contained before germination began.

In order to form an idea as to the meaning of this loss, let us imagine that we are engaged, not in the study of the physiology of plants, but in that of the physiology of motor-cars, and let us ask what we should require to learn before we could claim to understand the mechanism of cars. We should have to find out what uses the several parts serve, *i.e.* the functions of those parts, and also how they contribute to the work of the car as a whole. But we should require to know more than this, namely, the source of the energy which serves to drive the mechanism. If only from the smell left in their wake, we are familiar already with the fact that most cars consume petrol. We know also that the petrol poured into the tank of the car has to be replenished at intervals, and that, the faster the car is driven, the quicker is the petrol consumed. We conclude that the petrol furnishes the energy which drives the car. We find in the car arrangements for heating the petrol and for mixing it with the oxygen of the air so as to cause it to undergo combustion—that is, to unite chemically with the oxygen. As a result of this combustion, the petrol disappears, being replaced by waste, oxidised substances formed by the union of the constituent elements of petrol with oxygen. It is not, however, to produce these waste substances that the motorist purchases petrol. The waste substances are the unavoidable consequences of the combustion, and have to be got rid of. It is the energy liberated during the combustion that the motorist requires and employs, by means of appropriate mechanical devices, to do the work of propelling his car. If we burn a little petrol in a lamp, we find that energy, in the form of heat and light, is produced, that the petrol disappears, and that gases, carbon dioxide and water vapour, are given off. If we shut off the supply of oxygen completely, the petrol fails to burn, if we reduce the supply of oxygen, it burns with a smoky flame—the combustion is incomplete—and some of the carbon of the petrol, instead of uniting

with oxygen to form carbon dioxide, is deposited as soot The energy liberated during the combustion of the petrol in the lamp may be caused to do mechanical work, to convert water into steam, to make the heavy lid of a kettle containing water heated over the flame of the lamp to bob up and down so also the energy liberated during the combustion of the petrol in the car is caused to do the work of propulsion

Now petrol consists of a mixture of substances having the general formula, C_nH_{2n+2}, and when it is burned completely it gives rise to water and carbon dioxide Moreover, it can be proved experimentally that a definite amount of petrol unites with a definite amount of oxygen, and, as the result of its complete combustion to carbon dioxide and water, liberates a definite amount of energy Further, whether the oxidation is slow and carried out in several stages, or whether it is rapid and carried out apparently in one stage, the amount of energy liberated is the same Just as we pour a pint of water from a pot, either in a rush or drop by drop, and in either case get no more and no less than a pint, so the energy liberated by the oxidation of a given amount of a substance is fixed in amount, no matter whether it is liberated in one or more stages

If we turn our attention again to the seedling, we recognise as we note its root penetrating into the soil, its stem lifting itself into the air, its protoplasts dividing and laying down new partitions of cell-wall substance between the daughter protoplasts, that the plant, like the motor in action, is doing work But to do work is to expend energy From what source does the plant derive the energy necessary to carry on the work of living? The loss in dry weight undergone by the seed during germination now becomes significant The liberation of energy by the combustion of petrol in the motor-car, or in the lamp, involves a consumption of petrol and of oxygen The activity of the germinating seed involves a loss of substance May not this loss of substance be associated with the liberation of the energy by means of which the plant does its work? And further, from the analogy with the working of the car, may not this energy be derived from the union of

certain substances contained in the seed with oxyg obtained from the air? Thus we arrive at an hypothe which is capable of verification, and which, moreover, de no violence to our knowledge of seedlings. For we kn already that a loss of substance, analogous to the loss petrol in the running car, occurs in the germinating see We know, moreover, that seeds contain substances capal of uniting readily with oxygen: for example, the oil of o seeds may be used for lighting purposes. A handful sifted sugar thrown on a smouldering fire burns with bright flame. It seems reasonable to suppose, therefo that the reserve food-materials supply the materi for the process, akin to combustion, in the course which energy is furnished to the plant. But if th or something like this, is the mode whereby the pla derives energy, we shall expect to find that in doing so consumes oxygen, just as the petrol-engine consumes ox gen. Thus, we may test our hypothesis by determining t relation of seeds to oxygen. If the seed depends for i supply of energy on the union of certain combustil materials with oxygen, and if the energy so derived giv the seedling its power of doing work, then, just as witho oxygen, the petrol will not burn and the car refuses run, so, without oxygen, seeds should refuse to germinat To determine whether or no this is the case, we proceed follows —

58 Obtain seeds which are capable of germinati under water—rice is good for the purpose, but not alwa easy to get in a living state. Failing the seeds of water- marsh-plants, onion seed will serve, though it only germ nates so far under water as to show the white tip of i radicle. Next, prepare a quantity of boiled water by th method described in the Appendix B. Into each of tw similar small flasks or beakers, one filled with unboiled, th other with boiled (and cooled) water, put a dozen grai of rice or other seeds known to germinate unde water. Pour carefully a thin layer of oil on the surfac of the boiled water in order to check absorption o oxygen from the air. Observe the seeds at intervals, an note that germination does not occur in the absence o oxygen.

The following more striking method of illustrating this dependence of germination on oxygen-supply is due to Dr F F Blackman —

59 Two large beakers are placed in a sink, soaked barley grains (about a dozen) are put in each, and a wide-mouthed funnel is inverted over the grains in each beaker The beakers are filled with water so that the grains are submerged One beaker is put under an open tap so that a constant stream of water passes down the neck of the funnel and overflows from the top of the beaker

To the other beaker, no fresh water is supplied Hence the grains in the first beaker receive a constant supply of oxygen dissolved in the water of the stream and those in the other receive only such supplies of oxygen as are contained in the water in the beaker, or are absorbed by the water from the air In the course of a week or so, the barley in the continuous water-stream, although submerged, germinates and puts forth green leaves which grow to a considerable size, that in the standing water, though germination may begin, is unable, in the absence of sufficient oxygen, to produce any but the most diminutive of seedlings

In addition to these methods, the following experiments may be employed to demonstrate that oxygen is necessary for germination —

60 Fill two gas jars with water and invert them so that their open ends are downward and beneath the surface of the water in a pneumatic trough or large dish Displace the water by carbon dioxide (Appendix B) Impale two soaked bean seeds on a long blanket- or hat-pin Fix the pin to the inner surface of a cork which fits the mouth of the jar, and then push the cork with pin and seeds into the open end of one of the gas jars, keeping the lower end of the jar under water during the operation Proceed in a similar manner with the second jar, but before pushing its cork home, introduce, by means of a pipette, a little air into the jar

Leave the jars standing in the water in the dish or pneumatic trough to prevent any air from entering, and proceed in a similar manner to prepare two jars containing each, two soaked, impaled bean seeds Replace the water

in each jar by hydrogen (Appendix B), and, having so, allow a little air to enter one of the jars, since, howe hydrogen and oxygen form, in certain proportions, an plosive mixture, the hydrogen experiment should be om by those unaccustomed to chemical manipulation. Ins of hydrogen, nitrogen gas (Appendix B) may be emplo

As a contrast, set up a similar gas jar containing and pass soaked beans, transfixed by a blanket-pin, into jar. Record from day to day the germination of the s in the jars. From the fact that germination proc fairly uniformly in all the jars containing air, we k that the various gases (CO_2, H_2, etc.) do not of themse affect germination adversely, and since it proceeds no all, or at most very slightly, in the jars from which oxy is absent, we conclude that, as our hypothesis led u expect, oxygen is necessary for germination.

Another method which, though less direct, is interes because of its bearing on garden-practice, may be trie

61 Prepare enough puddled clay, by kneading clay with water, to fill two fair-sized marmalade pots a layer of the wet clay at the bottom of one pot, plac dozen barley grains, and press wet clay closely over t till the pot is full. Cover the pot with a sheet of gl Fill the second pot with puddled clay, and plant ba grains just below the surface. Cover each pot with a g plate. After a week or more, investigate the germina of the barley in the two pots. (The puddled clay mus prevented from drying during the course of the experim otherwise it will crack, and the experiment will fail. drying may be prevented by covering the two pots wit bell-jar, under which a saucer of water is placed.)

The results of the preceding experiments show that th can be no doubt that oxygen is necessary for germi tion. If we succeed in establishing our hypothesis, shall have the right to conclude that the failure of se to germinate in the absence of oxygen is due to the that, no combination between oxygen and combustible s stances being possible in these circumstances, no ene derived from this source is available, and no work can carried on. But if oxygen is used for this purpose, air in which seedlings are growing must in consequ

come to contain less oxygen By taking advantage of the well-known fact that a taper burns in ordinary air, but not in air free from oxygen, we can determine whether germinating seeds extract oxygen from the air

62 Half fill each of two wide-mouthed, well-stoppered bottles with soaked peas or barley Replace the stoppers and put the bottles in the dark in a warm place After twenty-four or forty-eight hours, bring *one* bottle into the room Having lit a taper, remove the stopper, and plunge the lighted taper into the air of the bottle The fact that the flame is extinguished gives us proof that oxygen has disappeared Since oxygen has disappeared from the air in which the seeds have germinated, it is in a high degree probable that it has entered into combination with some oxidisable substance contained in the seeds We will assume that this has been the case and also that the oxidisable substance is sugar Now a sugar, when burned, gives rise to carbon dioxide and water according to the equation —

$$C_{12}H_{22}O_{11} + 12O_2 = 12CO_2 + 11H_2O$$

Maltose = Malt sugar — Oxygen — Carbon dioxide — Water

Therefore, by ascertaining whether carbon dioxide is produced by germinating seeds, we have a method of testing the truth of the assumption which we have just made For the purpose of this test, we prepare a solution of lime-water or of baryta-water (see Appendix A), pass into a sample of either of these substances a stream of carbon dioxide from a CO_2-generating apparatus (Appendix B), and note that the lime-water (or baryta-water) becomes cloudy The cloudiness is due to the production of calcium (or barium) carbonate —

$$CaH_2O_2 + CO_2 = CaCO_3 + H_2O$$

By blowing through a glass tube, dipping into another sample of lime- or baryta-water in a test tube demonstrate that the air expired from the lungs is rich in carbon dioxide We now apply the test for CO_2 to the air in the second bottle of seeds which has remained in darkness remove

the stopper, pour in a quantity of lime-water, replace the stopper, and shake the bottle The marked turbidity of the liquid indicates that carbon dioxide (CO_2) was present in the air of the bottle in considerable quantity Since, however, ordinary air contains CO_2, it will be well to test a sample of air thus empty out the bottle, wash it, and then pour in lime- or baryta-water, replace the stopper, shake, and note that the amount of CO_2 enclosed in the bottle is sufficient to produce, not a heavy precipitate like that obtained before, but merely a faint cloudiness

The consumption of oxygen and the production of carbon dioxide by germinating seeds may be demonstrated in various other ways, *e g* —

63 (1) Prepare an apparatus (see Fig 15) consisting of a glass flask (*A*) fitted with a rubber cork By means of stout rubber tubing connect the side-tube of the flask with a glass tube of small bore (*B*), bent at right angles Introduce into the flask a piece of moist blotting-paper and also one or two dozen barley grains which are beginning to germinate Stand in the flask a tube containing a strong solution of potash (*C*), to absorb the carbon dioxide Replace the cork, warm the flask by dipping for a minute the lower part in water heated to about 40° C and place it so that the open end of the bent tube dips below the surface of mercury contained in a small vessel (*D*) As the air in the flask cools, it contracts, and the mercury rises up the tube to a certain height Mark the height to which it rises, either by making a line with india-ink on the tube or by reading off the level on a millimetre scale fixed behind the tube Cover the whole apparatus with a box or black cloth to exclude the light, and, at intervals, record the rise of the mercury in the tube The rise indicates that the total volume of gas in the flask and tube decreases We know from the preceding experiments that oxygen is used, and that carbon dioxide is produced by germinating seeds since the carbon dioxide is absorbed by the potash, the extent of the rise of the mercury in the tube gives an indication of the amount of oxygen consumed by the germinating seeds

Let us now review the situation to which this series of

experiments has led us We know that a germinating seed is doing work, and therefore expending energy We know that, in machines such as motor-cars, the driving energy is derived from the oxidation of petrol (or coal, or similar bodies) We know that, unless oxygen is supplied, the petrol cannot develop energy, nor can the seed germinate when oxygen is supplied, the petrol is consumed and the seed loses in dry weight: when the petrol is

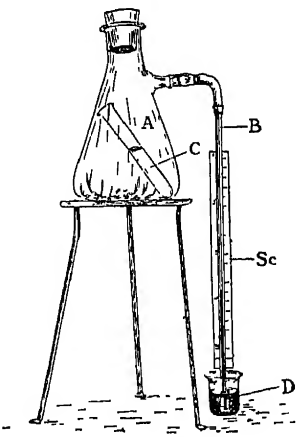

FIG 15.—APPARATUS TO DEMONSTRATE EVOLUTION OF CARBON DIOXIDE BY GERMINATING SEEDS

A, flask, with germinating seeds, B, glass tube, C, test tube containing potash, D, mercury, Sc, scale

oxidised, waste products, such as carbon dioxide, are liberated We cannot but conclude that the mode by which energy is obtained is similar in the motor-car and in the germinating seed, namely, by the union of oxygen with combustible materials and the consequent breaking-down of these relatively complex materials to simpler substances, such as carbon dioxide and water Nor is it difficult to obtain evidence to show that the materials oxidised in the germinating seed are, as we have assumed, the plastic food-materials If we look at the equation on p 69, show-

ing the mode of oxidation of sugar, we note th
number of molecules of oxygen consumed in oxid
molecule of malt sugar is equal to the number of m
of carbon dioxide produced in the process, and, si
molecules occupy the same space, it follows that,
oxidation of sugar, the volume of oxygen which disa
is equal to the volume of carbon dioxide produced
we have a means of testing whether, in a starchy
carbohydrate is the material, the oxidation of
liberates the driving energy whereby the plant-mac
kept at work

We use for the purpose the apparatus of Ex
making, however, the following modifications

64 A second flask of similar size and shape is
up and placed beside that containing germinating
If no potash is added to either flask, observation
that the mercury column, though its height may flu
owing to temperature-changes in the air, does no
in the same manner as in the previous experi
That such fluctuations as occur are to be attribu
changes of temperature causing expansion or contr
of the air in the flasks may be seen by observing tha
occur alike in the empty flask and in that cont
germinating seeds Inasmuch, therefore, as the v
of air contained in the flask in which the seeds are
sprouting undergoes little or no change, we may infe
the amount of oxygen consumed is about equal t
amount of carbon dioxide liberated by the seedlings

We conclude from the foregoing experiments th
starchy seeds, the carbohydrates supply the material v
when oxidised, yields the energy whereby the plant
its work Thus we have satisfied ourselves that the
food-substances which reach the embryo from the
sperm or cotyledons not only supply the protoplasm o
embryo with materials out of which is formed more p
plasm, but also serve as "combustible" materials b
oxidation of which the energy necessary for carryin
the life-work of the seedling is liberated We may s
of the processes whereby the plastic food-material
produced from the reserve-materials, and whereby the
incorporated with the protoplasm as the nutritive proce

or we may regard the former, digestive processes, as a preliminary to nutrition, and confine the term nutrition to the latter process only. If we adopt the second course, we require a term to include not only the digestive processes, but also other chemical changes which occur regularly in the living organism. We may use the term *metabolism* in this wide sense. To the process of oxidative decomposition of plastic food-substances—that is, the energy-producing process—the term *respiration* is applied. Since the whole significance of respiration lies in the liberation of energy, it is as absurd to say that respiration consists in the taking in of oxygen and the liberation of carbon dioxide as it is to say that a motor-car is driven by letting oxygen into the engine of the car and letting out carbon dioxide.

That the temperature at which respiration goes on in the seedling is far lower than that at which the petrol is burned in the car need not greatly trouble us. For, in the first place, chemists have shown that chemical reactions generally which go on at a high temperature, may go on, also, though at a slower rate, at a low temperature, and, in the second place, just as we found the enzyme, diastase doing at a low temperature what a trace of mineral acid could do with equal rapidity only at a high temperature, so it may be that enzyme-like bodies are excreted by the protoplasm for the special purpose of speeding up respiration.

There is still one aspect of the production of energy by the motor-car and by the seedling which requires attention. It is well known that the motor-car owes its existence to the improvements which have been made of recent years in the petrol-engine. The petrol-engine has been rendered more efficient by these improvements, that is to say, an increased percentage of the total energy developed by the combustion of the petrol is used for doing the work of propulsion. But, in spite of all the ingenuity expended on the construction of petrol, steam, and other engines, a very large proportion of the total energy produced is inevitably wasted—that is, is not used for the purpose which the engine is designed to serve. This wasted energy takes the form of heat, and the fact that it is wasted is due, of course, to no lack of skill on the part of engineers, but

to the properties of matter, *e g* to friction and to the power metals have of absorbing, conducting, and radiating heat, and so on If our comparison of the plant with a machine is just, we shall expect to find that, of the total energy produced in respiration, a large proportion is not employed in driving the plant's machinery, but appears in the form of heat That this is the case may be shown in a striking manner by the use of the familiar Dewar flasks (Thermo flasks) (Appendix B) As is well known, a hot substance put into a Dewar flask remains hot for a long time, and a cold substance remains cold

65 Soak in tepid water for twenty-four hours enough peas to nearly fill two Dewar flasks Wash the seeds in running water, and reject any which seem bad Remove superfluous water by means of a clean cloth or blotting-paper Nearly fill one flask with the seeds whilst filling, insert a small thermometer in the flask so that the part of the stem which records temperatures above 30° C only remains visible Push a large wad of dry cotton wool into the neck of the flask to close the neck and hold the thermometer in place Wrap the whole apparatus in a large, loosely-fitting jacket of cotton wool Boil the remaining peas, and, adopting similar precautions to those used with the unboiled peas, put half their number in the second Dewar flask with a thermometer and wad and covering of cotton wool Hang up a third thermometer in an ordinary flask to give the air-temperature during the course of the experiment During several days, and at as regular intervals as possible, record the temperatures registered by the three thermometers Observe that the germinating peas produce sufficient heat to raise the contents of the flask to a temperature as much as 10° C , or more, above that of the air Note that the temperature of the flask containing the boiled peas is for some time little above that of the air , but that, after a day or two, it may also show a rise of some degrees If it does, turn out the contents of this flask and observe that the peas have become mouldy Now take the remaining soaked peas and warm them for a few minutes in a beaker of water to which a trace of corrosive sublimate has been added It should be borne in mind that

corrosive sublimate is in the highest degree poisonous that only a mere trace need be added to the water in th beaker, and that the vessels which have contained it mus be thoroughly washed immediately after use If there i any objection to the use of corrosive sublimate, the pea may be boiled in a solution of permanganate of potas instead Rinse out the Dewar flask with a solution o corrosive sublimate or permanganate of potash Transfe the poisoned peas, after wiping them between sheets o blotting-paper, to the clean flask Arrange the ther mometer and cotton wool as before, and determine tha no mould being able to grow, no rise of temperatur occurs We learn from these experiments that germinat ing peas liberate a considerable amount of heat, an conclude that, just as in machines not all the energy i utilised for doing mechanical work, so, in germinatin seeds, some of the energy developed in respiration appear in the form of heat, and is therefore not used directly i doing vital work We learn, incidentally, that low form of plant-life, such as moulds, also produce heat, and w suspect that they too respire, and that they, like th seedling and the petrol- or steam-engine, are of only limite efficiency Under more natural conditions than thos which obtain in a Dewar flask, the temperature of ger minating seeds would, of course, not rise so high, for hea would be lost by conduction to surrounding objects Although we may regard the heat produced during ger mination as energy lost, in the sense that it is not applie to the performance of the work of the seedling, yet th heat may be serviceable in other ways, namely, in providin a temperature at which the organism can work at its best If the petrol in a car is frozen, the car cannot be started if the temperature of the car rises above a certain point damage ensues In other words, the mechanism of th car works only within a certain range of temperature That this is also the case with the seedling, we have alread determined in part for we know that seeds heated to th boiling point of water are killed

66 By exposing seed in germinators to different tem peratures, *e g* freezing point, room temperature, 25°-30° C and so on, we may determine that germination proceed

best at a certain (moderately high) temperature like machines in general, the plant-mechanism work under certain definite temperature-conditions.

The facts we have learned respecting the nutritio respiration of seeds are fundamental facts. They us that the living substance (protoplasm) owes crease to the plastic food-materials, and they c the source and mode of liberation of the energy w the living mechanism works. Therefore, if we ho to our general hypothesis which has helped us so already, and according to which the vital proces plants and animals are fundamentally similar, we expect to find that the modes of nutrition and of resp of the mature plant and of the animal are those germinating seed. The proof that this is the cas respect to nutrition we will defer to Chapter VI., an deal at once with respiration. With respect to an the necessary proofs lie close at hand. We have a traced the plastic food-materials to the blood-stream know that the multitudinous protoplasts which ma the body are bathed with fluid derived from that s We are aware that the body of the animal is cons doing work, and therefore expending energy. We moreover, that, in the warm-blooded animals, heat i duced in sufficient quantity to maintain the temperat the body at a remarkably constant level and consid above that of the surrounding air. We breathe on a ray or a piece of glass and note the water which come from our breath, we blow through a tube into lime and demonstrate, by the precipitate of calcium carb which forms, that the air we expire contains carbon di Putting these facts together, we recognise that the re tion of animals is similar to that of plants. The apparent difference consists in this, that the waste pro of animal metabolism include not only water and c dioxide, but also nitrogenous substances—urea, uric etc. Since these substances are evidently derived proteins, we are bound to infer that, in addition to c hydrates and fats, proteins also contribute, by their d position, to the energy required by the organism fo purposes of its life-work. In point of fact, pr

decompositions similar to those which take place in animals are known to occur in plants We may perhaps express the facts thus the bulk of the energy which is used by plant and animal is derived from the oxidative decomposition of carbohydrates or fats In the course of its activity, the protoplasm itself wears out, and so produces waste nitrogenous substances If plentiful supplies of proteins are at the disposal of the organism, as is the case with many animals and some plants, the proteins may be respired, *i e* they may be split up, certain of their products oxidised, and thus release energy The only difference between the animal and plant with respect to these energy-releasing processes appears to be that, whereas many animals are protein-spendthrifts, most plants are protein-misers This is a matter which, though interesting, is not essential, and need not therefore detain us With respect to the respiration of the adult plant, we convince ourselves by the following experiments that what we have learned from the seedling applies word for word to the adult

67 Grow two bean plants, each with its roots in tap-water contained in a wide-mouthed jar When they have passed the seedling stage compare the plants as to root and shoot development, and then remove one of them from the jar and place it with its roots in another jar containing boiled water (Appendix B) A layer of oil is then placed on the surface of the water in this jar The growth of the "transplanted" plant at once falls behind that of the untouched plant In the absence of oxygen from the water the energy necessary for the growth of the root is not developed By repeating Exp 62, using the opening buds of horse-chestnut or dandelion, etc , we prove that, like the seedlings, these parts of the mature plant absorb oxygen and evolve carbon dioxide By the method of Exp 65, using buds or young leaves, we demonstrate that their respiration results in a production of heat Thus we conclude that the energy-liberating processes, which we include under the term respiration, run the same course in both young and adult plants, and in animals We conclude, in fact, that this process is general in all organisms, and that if there are any organisms in which respiration

does not take place in this way, they must be regarded constituting special cases, and must receive spe consideration

CHAPTER VI

THE seedling as an independent plant the lowest forms of plants and animals and the lines followed in the evolution of the higher plants and animals The distinguishing characters of root- and shoot-systems The mode of growth of the root the functions of its parts the root hairs, the absorbent organs of the root

THERE comes a time when the seedling, reared hitherto at the expense of the reserve-materials of the seed, cuts itself adrift from the latter and sets out on its career as an independent plant That career we will now follow The independent seedling grows, forms new members, performs remarkable movements, and becoming a fully grown-up plant, bears flowers and sets seed For these operations, it must be able to obtain large supplies of material, and, for them, no small amount of energy is required We have learned by experiment what substances the young plant and the animal use in constructing their tissues and how they obtain their supplies of energy, so, till we find that the hypothesis is wrong, we will maintain that the mature plant uses similar food-materials for its nutrition Since, however, the substances, such as sugar, proteins, etc, which, on this hypothesis, constitute the true food-materials of organisms, are not present in the soil or in the air, it follows that either our hypothesis is wrong, or that the mature plant manufactures these plastic food-materials from other substances which it obtains from the soil or air, or from both these sources

68 The following experiment affords evidence in support of our hypothesis —

Germinate two lots of radish seeds on damp blotting-paper When the seedlings have emerged, grow one lot with the roots in clean tap water, the other lot in tap

water to which has been added a *trace* of potassium nitrate It will be found that the seedlings with their roots in the water to which potassium nitrate has been added grow far more vigorously than those whose roots are in ordinary water (Fig 16)

What relation, if any, exists between the absorption of such a mineral salt as potassium nitrate (KNO_3) and the formation of plastic food-materials need not concern us now We are content to note the evidence supporting the view that the root absorbs substances from the soil, and that these substances contribute in some way to the formation of plastic food-materials on which the growth and activity of the plant depend Recognising, as we must, the vital importance of plastic food-substances, it will be evident that the first and constant care of the plant must be to obtain adequate supplies of the raw materials which it needs for their construction, and, if we bear in mind what we have learned already with respect to the phenomenon of adaptation—the automatic adjustment of the members of an organism to their special work—(p 22) we shall expect to find that the plant-members concerned in the absorption of the raw materials of the food show adaptations tending to fit them for this work That is, these members, or parts of them, present appearances which we may recognise as fitting them to serve as *absorptive organs* Hence, by a careful and intelligent inspection of the members of a plant (roots, leaves, etc), we shall obtain broad hints of the special functions which these members or their parts perform

Our task, therefore, in this and in succeeding chapters is to discover what are the raw materials of the food, how they are absorbed, and how, from the raw materials, the plant manufactures the finished articles, the plastic food-substances such as sugar and proteins, on which the protoplasm subsists and on which, therefore, all growth and activity depend In studying these problems, we shall learn how profoundly the form characteristic of plants is determined by the necessity under which they labour of producing organs suited for the absorption of the raw materials of the food We shall even discover that in this necessity lies the origin of the remarkable

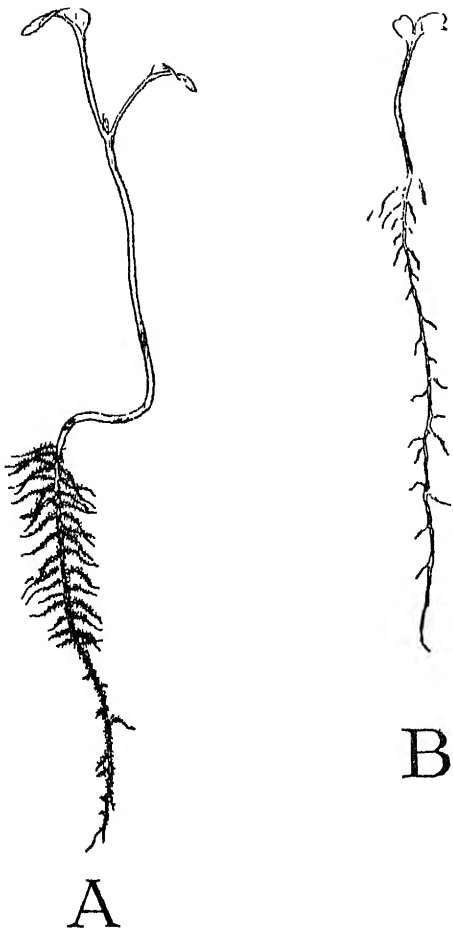

FIG 16

A, Radish seedling grown in tap water, to which has been added a trace of potassium nitrate; B, radish seedling, of the same age as A, grown in tap water only

differences in form which distinguish the higher plants from the higher animals Between animals and plants there are, as the evidence of former and later chapters proves, no fundamental differences except those arising from the obligation laid upon the plant to make its own plastic food-materials The modes of nutrition of the protoplasm are identical in plant and animal the respiratory processes are similar the movements, though more conspicuous in the animal, are alike, and the modes of behaviour to external influences are the same All the wonderful differences in form which stand out when we compare the animal and vegetable kingdoms are the outcome of this great fact that plants make their plastic food-materials, animals appropriate them ready-made It is a fact of the profoundest physiological importance that "all flesh is grass"

Let us, in order to illustrate these remarks, compare one of the lowest plants with a very simple organism which, though undoubtedly an animal, stands very near the parting of the ways which lead respectively towards the animal and the vegetable kingdoms The plant may be obtained often in great numbers in ponds, water-butts or rain puddles the animal is found also in these situations If water from one of these sources is stood in a glass dish near a window the presence of the plant and of the animal may be revealed by a green scum appearing on the side of the dish near the window On microscopic examination of a drop of the liquid, minute green organisms in active, dashing movement may be observed Now and again one of them rests awhile and then may be examined in greater detail It consists of a single protoplast the greater part of which is not colourless like that of the yeast plant, but green, the green part having a somewhat cup-shaped form (Fig 17 A) In the narrow cavity of the "cup," the protoplasm is colourless, and, by suitable modes of preparation, a denser, more or less spherical part of the protoplasm—the nucleus—may be seen lying toward the lower end of this neck of protoplasm At the free end of the neck is a slight projection or knob, from which extend two protoplasmic threads (flagella), each as long, or longer, than the body It is by means of the flagella

that the organism rows itself along On one side of the body, near the anterior end, a red speck—the eye-spot—may be seen; and suitably stained microscope-preparations show that the protoplast is enclosed by a delicate wall of cellulose, through which only the flagella project By hunting through drops of water obtained from puddles of rain water—and if the student has a microscope at his disposal the hunt is well worth making—examples of the second organism may be obtained It consists of a single green protoplast, which has the form of an elongated cup or flask (Fig 17 B), but instead of the narrow neck being occupied by colourless protoplasm, it is hollow, and thus forms a gullet Flagella, attached near the bottom of the gullet, project beyond the body of the animal As in Chlamydomonas—the plant previously examined—so in this animal, Euglena viridis, a nucleus and an eye-spot are present, but, unlike that of the plant, the enclosing wall of the body of Euglena is not of cellulose Upon occasion, both Chlamydomonas and Euglena may lose their green colour, become colourless and yet increase in size and even multiply by division So alike are the two organisms, that it might seem mere hair-splitting to describe the one as a plant and the other as an animal Nevertheless, it is proper and useful to distinguish them in this manner, for, it is possible to imagine that, by a long series of changes, all of the nature of so many adjustments to the more adequate winning of raw material from water or from land, or to the more efficient elaboration of plastic food-substances from this raw material, the higher plants, even the highest flowering plants, have been derived from a Chlamydomonas-like ancestor So it is conceivable, also, that all animals have been derived from some lowly form not far removed from Euglena viridis What then is the essentially plant-like character of Chlamydomonas, and what the essentially animal-like character of Euglena? Chlamydomonas encloses its protoplast within a definite wall of cellulose Euglena has a sac or gullet open to the outside Hence Euglena can engulf solid particles, digest them, and so obtain plastic food-substances Chlamydomonas debars itself from all solid food supplies, for only substances in

solution can pass its wall. Euglena can, upon occasion, prey on other organisms, and pick up nutritious morsels. Chlamydomonas cannot. Chlamydomonas, by surrounding itself completely by a wall, condemns itself to the labour of constructing its plastic food-substances from such soluble raw materials as its environment provides. Euglena, though

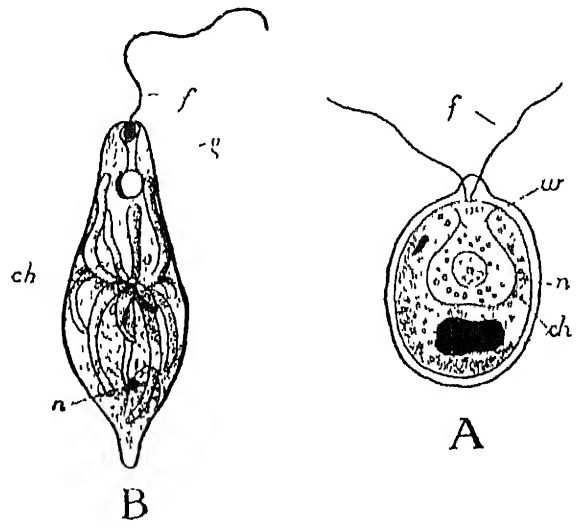

FIG. 17

A, Chlamydomonas pulvisculus; B, Euglena viridis. (Highly magnified.)
w, wall; ch, chloroplast; n, nucleus; f, flagellum; g, gullet.

it has not lost this power altogether (see Chapter XI), can swallow any likely particle, and thus get its food ready-made. These are the salient, differentiating characters not only of Chlamydomonas and of Euglena, but also of plants and animals in general. It is the investing wall which determines the mode of life of Chlamydomonas; it is the gullet which makes Euglena free of all solid food-supplies which it can engulf and digest. It is the fact that Chlamydomonas has a continuous solid cell-wall, which is the essential fact, not that the wall is of cellulose,

though, since it is of cellulose and since animal protoplasts have no cellulose walls, it is sometimes said that the cells of plants are characterised by cellulose walls, and those of animals by the absence thereof. Evidently this is true, but evidently also the wall is the thing, the chemical nature of the wall is a matter of less importance.

We may summarise the whole difference between Chlamydomonas and Euglena thus. Euglena would, if it could swallow it, feed on Chlamydomonas, Chlamydomonas cannot swallow, and, therefore, cannot feed upon Euglena, nor on any other undissolved substance. For "Euglena" write "animals," and for "Chlamydomonas" write "plants," and the statement holds good. Animals feed on plants, plants cannot feed on animals unless, as happens in the case of certain parasites, a plant gets access to the soluble substances contained in the body of an animal.

Our excursion into the world of microscopic plants and animals has been of use, not only in presenting our immediate problems to us more definitely, but also in enabling us to take a more comprehensive view of the plant and animal kingdoms.

We return now to the work of flowering plants, and proceed to enquire into the nature and mode of absorption of the raw materials of their food.

It is a significant fact that plants in general live, as it were, in two worlds. One-half of the plant leads a subterranean life, the other half an aerial life. It is noteworthy, also, that the underground root-system differs markedly in form and aspect from the above-ground shoot-system.

69. A careful examination of a young plant, *e.g.* sunflower or bean, etc., dug up from the soil or turned out from its pot, or, better, raised for the purpose in a box of coco-fibre or sawdust (Appendix B), shows us that, whereas the green shoot-system consists of a main axis bearing two kinds of lateral members, namely, lateral axes (branches) and leaves, the colourless, or non-green, root-system consists of a main axis (tap-root) bearing lateral members (lateral roots) of one kind only. Moreover, an examination of the lateral members of the root and shoot shows that they differ from one another with respect

to origin, structure, and behaviour Note, for example, each lateral shoot begins as a bud standing in the axil leaf (see p 18), that these axillary buds arise as sc what superficial outgrowths from the main axis, that e main and lateral shoot-axis terminates in a bud, that such a bud may develope into either leaf-bearing flower-bearing branches, now observe that the lateral r do not arise from buds, but push themselves out from deep-lying tissues of the main root, and that, instead terminating in a bud, each lateral root, like the main-r has over its tip a thin, brownish, thimble-like cover called a root-cap, nor are flowers borne on the root.

70 Beside observing these morphological differer between the members of the root- and shoot-syste we prove by the simple experiment of turning a plant on its side and leaving it in a horizontal posi for several days that remarkable physiological differer also exist between them Whereas, in consequence this change of position, the main stem or ascending curves till its young tip points once again vertically upw the main root (the descending axis) curves in precisely opposite manner till its tip points vertically downward

Whilst drawing the specimen, we note, also, that lateral members of root- and shoot-systems exhibit ch acteristically different curvatures as the result of this cha of position

When we study the curvatures of root and sh we recognise that they serve to bring the root i the soil and the shoot into the air If we observe animal making similarly purposeful movements, for stance, a worm thrusting its head out of its burrow, say that the movements are instinctive Now, in p of fact, certain fixed animals perform movements, response to change of position, quite like those of root and shoot of our plant Hence there is every rea for us to regard the upward and downward bending shoot and root respectively as examples of nervous acti of the same order as those which in animals are spo of as instinctive Like instinctive actions in general, th root- and shoot-curvatures serve evidently to secure well-being of the organism The well-being of the pl

then, is secured by the penetration of the root into the soil and by the exposure of the shoot to the air. In other words, the shoot has work to do which can best be done in the air, the root has work to do which it can perform best in the soil.

Thus we come to ask, what is the nature of the work performed by the root-system? The most commonplace observations suffice to convince us that the root-system of a plant serves to fix it firmly in the soil. The tree resists all but the most violent hurricanes, the place on the wall where last year's ivy grew is marked by the remains of the roots, which broke rather than relax their hold when the ivy was torn away, the delicate root of the tender seedling is held so firmly in the soil that the pull of the shoot extricating itself from the seed does not disturb it. We must discover by what peculiar mode of growth the root, though elongating all the while, maintains its hold upon the earth, and so serves as a support to the plant.

71. To this end we choose several germinating bean seeds, the roots of which are about 1-1½ inches long. The seeds for the experiment may be germinated either in moist air, or, since roots often fail to grow straight in air, in boxes of moistened coco-fibre or of sawdust. Dry with blotting-paper the surface of a straight root about 1-1½ inches long, and, by means of the method given in Appendix B, make a series of 10-12 india-ink marks at distances of about 1 mm. from one another, starting from the tip of the root. Lay a millimetre scale beside the root, measure, and record the distances between the consecutive marks. Pin the seedling in moist air, or, when the ink is dry, replant it in a seedling "observation-box" (Appendix B) in moist coco-fibre or sawdust, with its root vertically downward and so near to the glass face as to be visible from the outside of the box. Measure, at intervals of twelve or twenty-four hours, the amount of elongation of the several marked zones. Tabulate the results and plot them in the form of a curve. Determine that the elongating region begins about 1 mm. behind the root apex, extends over a very short section (10-20 mm.), and ends near that part of the root where the root-

hairs begin. Note also that, further back, the root, tho it has ceased to grow in length, increases in thickn Measure the distance from the apex of the region maximal elongation

72 ' Cut longitudinal sections through the root-tip through the region of greatest elongation note (if ne salty staining with iodine) that the cells of the former re are small, and that the protoplasm occupies the whole of cell, that the cells of the latter are large, that the pr plasm forms a layer against the cell-wall, and that it i encloses a large space (vacuole) containing liquid (cf p Fig 20) Observe that, when treated with iodine, protoplasm, which is killed by the reagent, contracts a from the wall, and, staining yellow or yellow-brown, comes readily recognisable The extreme tip just beno the root cap, composed of small cells with much pr plasm, constitutes the formative region, *i e* the reg where the protoplasts are undergoing division, and t forming new protoplasts Behind the small forma region (of about 1 mm) is the region of elonga (some 20 mm in length), and in this region, where sc cell-division also occurs, the increase in length of whole root is effected by that of the constituent ce We can now understand how, from the very start, growth of the root makes for the steadiness of the p and secures its fixation The old part of the root—the p in connection with the stem—having ceased to elongate wedged, as in a vice, in the soil Nor does the tip elong The growth in length of the region behind the tip res in a pressure which, since the apical region is free to mo drives the tip through the soil, the shortness of the el gating region serves to prevent that region, in the even the tip meeting with considerable resistance, from be itself bent Each day, a section ceases to elongate, each day, a newly formed region just behind the growi point begins to increase in length Somewhat in the v that a worm, fixed by its tail-end, pushes, by the elongat of its body, its head from a burrow, a root pushes its through the soil

73 By the use of a seedling observation-box, on glass front of which we trace each day the outline of

roots, we follow the course of elongation of the main and lateral roots of a bean or pea seedling

We learn from these observations that each root consists of the following regions a formative region (growing-point) covered by the root cap, a region of elongation, a region of thickening, the lower part of which constitutes the root-hair region

74 In order to compare the mode of elongation of the shoot with that of the root, mark the young shoot of a seedling bean or pea, from base to apex, with a series of india-ink marks about 8 mm distant from one another Proceeding as in the case of the root, determine the amount and distribution of the growth of the marked shoot We thus discover that the growing region of the shoot is as extensive as that of the root is limited that, in the young stem, parts far distant from the apex, as well as parts near it, are in active elongation that the parts which elongate most rapidly are situated between the nodes, *i e* the places of insertion of the leaves, and that therefore these internodal regions come each to be of considerable length The stem in cleaving the thin air encounters but slight resistance, and is therefore under no necessity, as is the root, to concentrate its elongating region

The significance of the root-cap now becomes evident Behind it, lies the delicate growing-point, in front, are grains of sand, small stones and other hard substances of the soil which the tip is bound to encounter As a thimble protects the finger, so the root-cap protects the growing-point of the root It can be shown, moreover, by simple experiment that the root-tip has another and more subtle means of protecting itself from mechanical injury

75 Plant bean seeds in a seedling observation-box containing, beside coco-fibre, a layer of small stones on the top of which more coco-fibre, in which the seeds are planted, is laid and pressed down Follow the behaviour of the roots when they come to the layer of pebbles Note that, when obstructed, the root curves in such a way that the tip is first moved away from the obstruction, and then, brought again into the vertical position, resumes its downward progress. Determine that the curvature in

response to contact and that which results in the resti tion of the vertical position, take place, not at the itself, but in the region of elongation Some of plants raised for the purpose of the above experim may be allowed to grow on, in order that the origin order of development of the lateral roots may be obser As already indicated, the lateral roots are identical in st ture with the main root, and grow in precisely the s manner Thus each lateral root, wedged like the r root firmly in the soil, contributes to the firm hold whicl whole root-system has on the soil

76 Onion or hyacinth bulbs, started into growt hyacinth glasses, or similar vessels filled with water, vide objects for the study and the development of ano type of root-system Observe that a number of indepen roots which, since they arise on the bulbous stem (at base), are called adventitious roots, make their appear and grow all at about the same rate Examine the r systems of several Dicotyledons and Monocotyledons refer them to the bean type (tap root-system, cf Fig or to the onion or lily type (adventitious root-system, 19) Note also cases (*e g* sunflower) in which the tap soon ceases to grow, its place being taken by numer true, lateral roots (fibrous roots) Observe that pl with a tap root are deep-rooting (mallow, etc), tl with the adventitious types of root are more surf rooting Note the curious behaviour of the roots of var rosette plants (dandelion and plantain), which, after p trating the soil to a certain depth, shorten so much a throw the outer tissues of their older parts into transv folds, and observe that, as a consequence, the rosett leaves and the epicotyl are dragged down close to ground Note, on a lawn, how the plantain and the dar lion, by this root-contraction, press down the grass in t neighbourhood, and so secure space and light for th selves

77 Dig up a dandelion plant Cut its roots lengths plant the pieces of root in moist, sifted Observe that, after some weeks, each root has develo into a plant Follow the process by which this comes ab Note that the wounded, cut surfaces are made smooth

healed by the formation of tissue, called callus or wound-tissue, that, later, roots develope from the new tissue of the lower end, and that buds, which are called adventitious buds, develope from the new tissue of the upper end We conclude, therefore, that the morphological 'points" (p 85), which distinguish roots from shoots, *e g* that the root does not bear buds, are the expression of general, but not of irrevocably fixed habits on the part of these members We note, in confirmation, that many trees, *e g* elm, may throw up suckers from injured places on their more superficial roots

78 In order to study further the process of healing of wounds and the formation of adventitious roots from callus-tissue, cuttings of geranium, willow, rose, etc , should be made, planted, and examined in their different stages of growth mount a typical series of such cuttings, and add them to the museum Observe and record the healing of wounds made when large branches are lopped from trees If possible, obtain a series of photographs of such wounds and of the appearances they present in the slow course of their healing put the date and other details on the photographs, mount them, and add them to the museum

Having studied the fixing function of the root-system, we must next direct our attention to an even more fundamental part of its work, that of absorbing substances from the soil From general knowledge of plants and gardens, such as the wilting and dying of plants in periods of drought, and from the large percentage of water contained in plant-tissues (see Exp 5), we are bound to infer that a plant absorbs water from the soil We shall have an opportunity later (Chapter IX) of determining the quantities of water taken up by the roots, and will now confine ourselves to enquiring how the absorption of water is effected

When growing hyacinth or tulip bulbs in water in hyacinth glasses for the purpose of Exp 76, it may have happened that, owing to neglect in keeping the glasses quite full of water, the later-formed roots found themselves compelled to grow some distance through the air before reaching the water If such was the case, it may have

FIG 18

Broad bean (Vicia Faba) Root system of seedling, showing elongation of the radicle to form a tap root (r) with numerous lateral roots (lr)

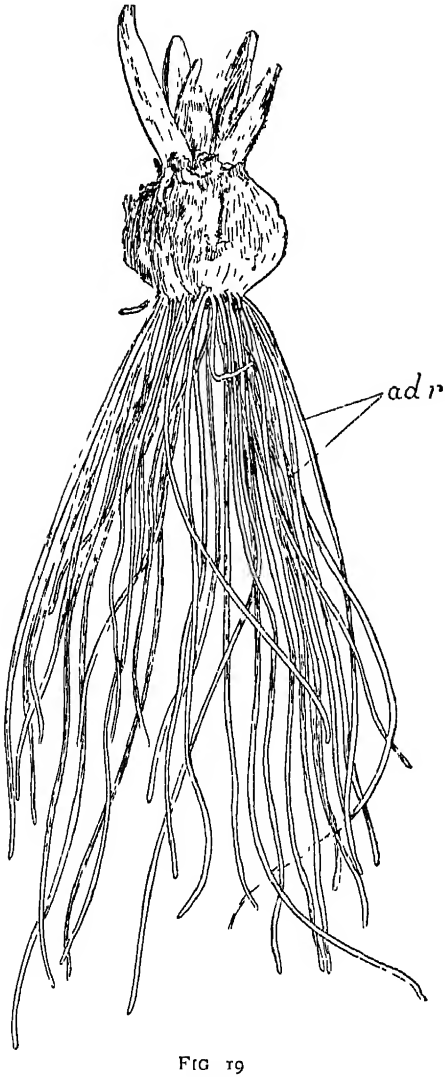

FIG 19
Hyacinth (Hyacinthus orientalis) Bulb with adventitious root system,

been noticed that, whereas the surfaces of the roots which were submerged from the first are quite smooth, those of the roots which grow through the air are covered with fine, white root-hairs

In order to obtain material for the study of this phenomenon, we germinate oat or bean seeds, some with their roots in water, others with their roots in moist air

79 * Make transverse sections across the beginning of the root-hair region of a root growing in air, mount in water, and examine under the microscope Observe, with low and high powers, the root-hairs in all stages of development Put the preparations aside and make others through the corresponding regions of a root grown in water which presents to the naked eye no sign of root-hairs Determine, by microscopic examination of the sections, that slight, dome-shaped outgrowths from the superficial cells occur, and that they are identical with those on the youngest part of the root-hair region of the root grown in moist air

80 Germinate two lots of maize or oat grains, one, so that the young roots are in moist air, the other, so that they are in moist sand or sawdust Contrast the development of the root-hairs in the two cases If, now, we assume that the plant possesses a certain power of regulating the development of its organs in accordance with external conditions, we are led to infer from these facts that the root in water or thoroughly wet soil, being able to carry on its work without their help, does not put itself to the trouble of forming root-hairs Since, however, countless generations of plants have required root-hairs and have formed them, these plants—like land-plants in general—have acquired the fixed habit of producing root-hairs Hence a hyacinth or bean root in water is, as it were, the subject of divided counsel The ingrained habit urges the formation of root-hairs They begin to form The presence of much water renders root-hairs unnecessary They cease to develope We may suppose that the formation of the incipient root-hairs is due to habit, but that the root, before it obeys the dictates of habit, requires a special stimulus, perhaps, in this case, a slight drying of its surface In water, this stimulus is lacking, and the

root-hairs never get beyond the rudimentary stage The bodies of plants and of animals contain many rudimentary structures the calyx of the flowers of the daisy family is often represented by mere hair-like structures whales and various snakes have hind limbs which are ridiculously small, and are never used our ears have sets of muscles which do not work the vermiform appendix, the rudiment of an accessory stomach, is a nuisance The hypothesis just suggested to account for the rudimentary root-hairs of the water-roots of hyacinths helps us, when applied to these cases, to form some idea why rudimentary organs may outlive their uses The habit of laying them down belongs to the race the business of their further development, to the individual This further development depends on some precise stimulus either from without or from within In the absence, more or less complete, of this stimulus, the organ remains rudimentary

Our observations on the presence or absence of hairs on the hyacinth roots lead us to conjecture confidently that the root-hairs are organs which serve to secure the absorption of ample supplies of water We argue thus roots grown in water have access to plentiful supplies, roots in moist air to but meagre supplies of water If the special business of the root-hairs is to secure an adequate amount of water, then, in the case of water-roots, root-hairs will have but little to do, but in the case of air-roots, their water-absorbing capacities will be exercised to their full extent

81 We test this hypothesis by an examination of the roots of various water-plants, and discover that, in the large majority, *e g* water buttercup (Ranunculus aquatilis, etc), root-hairs are absent though, in the case of some aquatic plants, such as the frog-bit (Hydrocharis Morsus-ranae), root-hairs are produced in large numbers (The aquatic plants collected for this purpose may be examined also with respect to their shoot- and root-systems, which should be compared with those of land-plants, and, with examples of the latter, dried and preserved in the museum, together with notes of their several characters)

We may take it, then, as probable that the function of root-hairs is to secure a plentiful supply of water for the

plant, that, when the root finds itself in water or wet
the root-hairs are not required, and may remain rudi
tary, but, when the root is in ordinary soil, in which t
is no excess of moisture, root-hairs develope and play
important part in the work of water-absorption

A naked-eye examination of root-hairs suffices
show that they are extremely delicate structures
microscopic examination confirms this How deli
they are we demonstrate by pulling up and expo
several of the oat or maize seedlings (of Exp
to the dry air of a room We observe that the r
hairs soon shrivel and die Herein lies the expla
tion of the reason why gardeners, when transplan
seedlings, and indeed any actively-growing plants,
careful to perform the operation quickly, and to leav
ball of earth attached to the root for, otherwise, the r
hairs are injured and the plant suffers owing to its inabi
till a new crop of root-hairs is formed, to obtain adeq
supplies of water We can understand, also, why cutti
which have, of course, no special absorbent organs, l
to be planted in moist soil and protected from loss
water

82 The maize and oat seedlings of Exp 80 s
to show that root-hairs are not only delicate,
ephemeral structures By making sketches to s
of the roots daily, and indicating in the sketches
root-hair region, we discover that, although day after
the extent of the root-hair region remains fairly const
this is due, not to the permanence of the individual r
hairs, but to the formation of new hairs, just behind
elongating region, to take the place of those which,
the side distant from that region, are shrivelling and dy
Each day, the root-hairs in the older part of the root-
region wither, and, each day, others are formed in
younger part of that region If, therefore, we detern
the time that the root takes to increase its length by
amount equal to that of the root-hair region, we h
determined also the average length of life of a root-h
By measurements of this kind we discover that the life
a root-hair is generally a matter of a day or two S
the root of a plant bears root-hairs throughout its

it follows that, during that period, countless numbers of root-hairs arise, do their work, and die

The evidence which we have brought together in support of the water-absorbing function of the root-hairs, though strong, is not direct We have now to attempt to prove definitely that a root-hair cell possesses the power of absorbing water, and, if we succeed in this, we shall have to enquire how the absorption of water is effected Our enquiry will necessitate the examination of root-hairs, and also other cellular elements of plants, and will give us information which will be of service to the understanding, not only of the mode of water-absorption by root-hairs, but also of many other phenomena exhibited by plants—as, for example, the method of growth of cells, the origin of the pressure exerted by roots in penetrating rigid soils, the means by which delicate seedlings hold themselves upright, and so on

83 ' We begin this work by making a more thorough examination of preparations of root-hairs (see Exp 79[3]) On examining them microscopically, we observe that the first sign of the root-hairs is a slight raising up or projection of the free, outer wall of a surface cell of the root-hair region We recognise that, since the cellulose wall of a cell is dead, the rounded projection must be due to pressure from within This pressure continuing, the cell-wall bulges outward till it forms a finger-like projection By treating preparations with iodine solution, we find that, as in all other protoplasts, that which constitutes the root-hair cell consists of a mass of protoplasm In the very young cell, the protoplasm forms a more or less dense mass, taking up practically the whole of the space occupied by the cell, but, in the older root-hair cell, the protoplasm, unrecognisable, perhaps, before the addition of the iodine solution, is seen, after its action, to form, and, indeed, to be confined to, a thin layer just beneath the cellulose wall Within this protoplasmic layer is a clear space or vacuole occupied by a watery fluid, the cell-sap (see Fig 20) As the action of the iodine continues, this layer, or film of protoplasm stains brown and contracts away from the wall

84 ' In the next place, in order to satisfy ourselves that

structures like root-hair cells are able to absorb wat
pull off some of the violet hairs which occur on th
ments of the stamens of Tradescantia virginiana, or, i
this material, we make sections parallel to the surf
the leaves of Primula sinensis (or cross sections of t
stem of this plant), surface sections of the petals of co
flowers or, if nothing better is obtainable, we us
sections of beetroot Our object in choosing such c
is to obtain cells which are similar in structure to roo
cells, but in which the cell-sap is coloured, and hence r
recognisable Examine microscopically and draw th
paration observe the cell-wall and vacuole with its co
sap and note that no protoplasm is to be seen No
in under the cover-glass a 5-10 % solution of common
or a 3-5 % solution of potassium nitrate (Appendix A)
that, as the salt solution passes into the cell, the co
sap of the vacuole contracts away from the wall and
to occupy a smaller space than before Since the v
contains fluid, and since fluids are incompressible, it f
that the addition of the salt solution has caused so
the liquid of the cell-sap to pass out from the va
But the space which now exists between the cell-wa
the coloured blob of cell-sap is colourless, a fact whic
cates that none of the dissolved pigment to which th
owes its colour has escaped from the vacuole By co
ing the appearance of the cell in water with th
the cell acted on by salt solutions of increasing str
(Fig 20), we are led to the conclusions (1) tha
vacuole is surrounded by a membrane through which
may pass, but through which the dissolved pi
does not pass (2) That, in the intact cell, the mem
is pressed close against the cellulose wall, in
position, owing to its thinness and transparency, i
be invisible We treat the sections in salt solution
iodine solution, and observe that the layer in question
the yellow-brown reaction characteristic of protop
As the action of the iodine continues, observe th
protoplasmic layer, now killed, shrinks away from th
wall, and, becoming disorganised, allows the conte
the vacuole to escape We may note, also, the d
stained nucleus lying either in the protoplasmic mem

or slung in bridles of protoplasm stretching across the cell from one part of the membrane to another

85 * Make another microscope preparation of the hairs of Tradescantia, etc., run in dilute salt solution, and, whilst the coloured sap is still enclosed in the protoplasmic layer of the cell, add a drop or two of water to one edge of the cover glass, and, by means of blotting-paper placed at the other edge, withdraw the salt solution so that the cell is

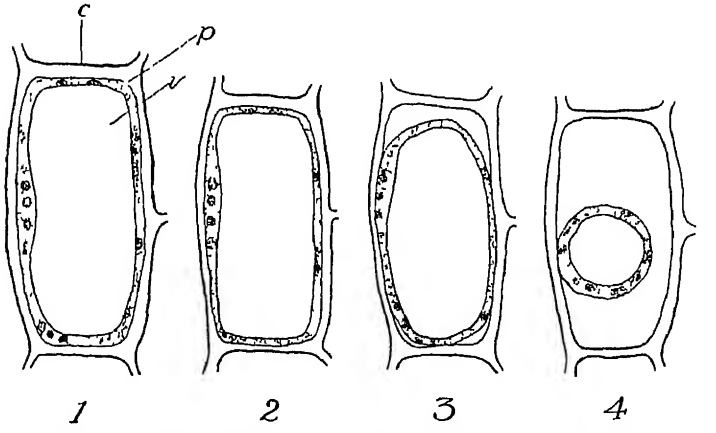

FIG 20.—YOUNG PLANT CELLS FROM THE TISSUE OF A FLOWER PEDUNCLE TO SHOW STAGES IN PLASMOLYSIS

1 In water 2 In ½ per cent solution of potassium nitrate 3 In 0 per cent solution of potassium nitrate 4 In 10 per cent solution of potassium nitrate *c*, cell wall, *p*, protoplasm, *v*, cell vacuole

(After De Vries)

again in water Note that the vacuole increases in size till once again its outline comes to lie close against the cell-wall We thus learn that, when the salt solution is replaced by water, the latter substance passes through the membrane of protoplasm (or plasmatic membrane as it is called) to the vacuole Thus, the volume of the cell-sap increases and, as a consequence, the membrane is stretched till it comes to lie close against the cellulose framework of the cell We infer that, just as salt solution withdraws

water from the vacuole, so something in the vacuole may cause water to pass into it from the outside

It follows from these facts that a vegetable cell is an apparatus of a remarkable nature, and that it consists of a protoplasmic layer across which water may pass, but across which other substances, *e g* dissolved pigment of the cell-sap contained in the vacuole, may be unable to pass This layer is stretchable Hence if water passes into the vacuole, the increased pressure thus set up stretches the protoplasmic membrane till it is pushed firmly against the cellulose wall Since also the cellulose cell-wall is stretchable—though less so than the protoplasmic membrane—if more water passes into the vacuole, the cell-wall itself is stretched and the cell becomes larger (cf Fig 20, 1 and 2) If, whilst the cell-wall is thus stretched, the protoplasm secretes a new layer of cellulose on the inner surface of the old layer, and if this new layer is sufficiently rigid to maintain the whole cell-wall in its present position without the help of the pressure of the cell-sap in the vacuole, then this distension of the cell by the fluid pressure of the vacuole is made permanent, and so, if now the protoplasmic membrane is caused to shrink away from the wall, the latter, being more rigid by reason of the new layer of cellulose, does not collapse as much as before There has been, therefore, a permanent increase in size of the cell· in other words, the cell has grown In the case of the root-hair cell, the stretching of the wall takes effect only at the dome-shaped projection which, in consequence, comes to form the tubular outgrowth characteristic of the root-hair

A living cell, the vacuole of which is so full of sap as to press the plasmatic membrane close against the cellulose wall of the cell and to stretch the latter to its full extent, is said to be turgid, and is described as being in a state of turgidity or turgor If water is withdrawn from the vacuole, as, for example, by exposing the cell to the action of salt solution, the volume of the cell-sap decreases and the vacuole becomes smaller The previously stretched protoplasmic membrane recoils, as a piece of stretched elastic recoils when released, and so contracts away from the cellulose wall A cell in this condition is

said to be plasmolysed, and the process by which this condition is reached is called plasmolysis The turgid cell may be compared with an inflated bicycle tyre, and the plasmolysed cell with a deflated tyre As in the inflated tyre, the pressure of the air in the inner tube distends its wall, presses it against that of the outer tube, and stretches the wall of that tube so that the tyre becomes rigid, so, in the turgid cell, the pressure of the fluid in the vacuole stretches its wall (the plasmatic membrane), and, pressing it against the cell-wall, stretches that wall so that the cell becomes rigid and as a reduction of air-pressure in the inner tube—due to escape of air—results in the recoil of the inner tube, and a relaxation of the distended outer tube, with the result that the tyre becomes flabby, so a reduction of fluid-pressure in the vacuole—due to loss of water—results in the contraction of the previously stretched plasmatic membrane, and consequently in a relaxation of the cell-wall, with the result that the cell loses its rigidity Consequently, if the elements of a cellular tissue are turgid, the tissue has a certain rigidity, if they are plasmolysed, the tissue becomes flabby

Since, for reasons which will appear presently, these matters of turgidity and of plasmolysis are of fundamental importance, we will determine by experiments on various plants that the facts we have learned from the study of cells with coloured sap hold good for living vegetable cells in general We note, for example, the supple sturdiness of delicate seedlings

86 Lay one or two cress seedlings on the table, and observe that, as they wither, they become flabby As they dry, the cells lose water and the protoplasmic membranes cease to press on the cellulose walls The walls are too delicate of themselves to form a sufficient scaffolding or skeleton for the plant, and the seedling is too young to have formed any supporting internal skeleton of woody tissue Hence the whole plant becomes soft and droops Note the wilting of leaves of plants in dry weather and infer the cause

87 Take two bean seedlings, each with roots about 2½ inches long, make on each an india-ink mark about 2 inches from the tip. record the exact distance between

mark and tip Plunge one root into a 3% and the o into a 10% solution of potassium nitrate, leave for sev hours note whether the roots have become flabby measure the distance between the tip and ink mark in e case Refer the contraction to plasmolysis Plunge roots into ordinary water. After some hours, remove measure them The root which was partially plasmol in the 3% solution has recovered its normal length has become turgid That subjected to 10% has not covered Plant both seedlings and determine that root of the former grows, but that of the latter does n having been killed by the stronger salt solution

88 Make an India-ink mark beyond the growing re of each of two bean roots growing in moist air Deter the rates of elongation of the roots Plunge one root 4% solution of potassium nitrate, the other into w. Determine that the root in water continues, and that in salt solution ceases, to grow in length Transpose roots and observe that the partial plasmolysis due to salt solution is sufficient to check growth: thus pro that turgor is a condition for growth

89 Cut two square chunks of beetroot of about e sizes Wipe their surfaces Plunge one into hot water, the other into cold water Note that the escapes from the former and not from the latter the es being due to the destruction of the protoplasmic membr Hence determine the approximate temperature at w the cells of the beet are killed

90 Cut a cucumber in slices, throw some of the sl on a plate, and cover them with salt after some ho compare their flabbiness with the natural firmness of treated slices Consider the influence of thus plasmoly a cucumber on its digestibility

91 Select several flower-stalks of dandelions bea open buds, remove the flower-head and split a stalk len wise into four sections note that the pieces curl so that inner tissue is outside Cut the curls into rings, th several into water, and note that the rings coil up in same sense as before The coiling in water is due to fact that the cells of the originally inner surface abs water, and so increase in volume, whereas those of

originally outer surface of the stalk absorb no water, or little, do not stretch, and hence are obliged, by the stretching of the inner rows of cells, to bend Make a model of wire and indiarubber tubing to illustrate this bending

Inasmuch as a tissue, when turgid, is longer, owing to the stretching of the cell-walls, than when it is plasmolysed, it follows that we can measure the amount of pressure necessary to produce this difference of length by first plasmolysing a piece of a plant consisting mainly of cellular tissue and then determining how big a pull is necessary to stretch it to its original length

92 A cowslip flower-stalk serves well for this purpose Two india-ink marks are made at about two inches distance from one another, the distance between the marks is measured accurately, and the stalk is put into a strong solution of potassium nitrate (15 %) When the stem has become flabby, the amount of contraction is determined by remeasuring the distance between the marks The stalk is then laid horizontally on a plate of cork or wood, one end, just beyond an ink mark, is fixed securely to the plate by means of pins or thin nails, and to the other end, just beyond the other mark, a stout thread is tied, the thread is passed over a simple pulley fixed to the edge of the table and attached to a scale pan taken from a chemical balance By placing a millimetre scale beside the stalk, and by adding weights to the scale pan, determine the weight required to stretch the stalk to its original length To express the result more definitely, measure, *e g* by means of a microscope provided with a micrometer (Appendix A), the area of a cross-section of the stalk at the beginning of the experiment, and, neglecting the fact that the stalk is made up of a vast number of cells, consider it as a single cell and argue thus —the pull on the end walls necessary to stretch the plasmolysed stalk to its original length is so much · but this original length of the turgid stalk was maintained by the pressure of the cell-sap in the vacuole therefore, the latter pressure, causing turgor, is equal to the mechanical pull due to the weights on the scale pan since we know the area of the cross-section we can express this pressure in pounds per square inch and since we know that the atmosphere exerts a pressure of about 22 lbs

to the square inch, we can express the turgor-pressure i terms of atmospheric pressure, *e g* as equal to 1, 2, 4, 5, or more atmospheres By means of measurement made in this and other ways, it has been found that th turgor-pressure in plant-tissues may be very great indeed reaching as much as 10, or, in some cases, even 20 atmo spheres It is by reason of these great pressures tha relatively delicate plant-structures may, when they en counter obstacles to their growth, perform remarkabl feats of strength thus they may cleave rocks or, like th thistles of the American prairies, raise up and bend railwa lines

Our investigation of the mode of absorption of water b the root-hair cell has carried us a long way from ou immediate subject, nevertheless, it has not been irrelevant For it is evident that, just as the partially plasmolysed cel of Exp 85* absorbs water and recovers its turgidity, so ma a root-hair cell absorb water and become distended I a cell neighbouring on a root-hair cell has been losin water, it may withdraw water from the vacuole of th root-hair cell just as the salt solution withdraws water fron the turgid cell in Exp 84† Then the root-hair cell, having lost water to its neighbours, may take up from the soi more water to make good that loss In this way i obtained the large quantity of water absorbed by the root and in this way also the water, thus obtained, passes from the root-hair cells into the wood-vessels of the root (Biblio graphy, 5, 6)

when the stopper is taken out of the bottle in which i contained The rapid dissemination of the odour is due less due to air currents which carry the odoriferous stance but, even if the air of the room was perfe still, the vapour given off by the scent would be distribu gradually throughout the space

In order to account for the phenomenon of gase diffusion, and also for other phenomena exhibited by ga a theory—the kinetic theory of gases—has been put ward, which suggests that, though, in any gas, there no visible mass movements, nevertheless the invis molecules are in a state of constant movement Apply this theory to liquids, we may suppose that, in a solu of salt, the molecules of salt are moving through the w in all directions like those of a gas liberated in the though, owing to some form of obstruction on the par the water molecules, not so freely From this hypoth it should follow that if a solution of salt is brought contact with water without shaking, the salt molec travel gradually throughout the water till, ultimately, t become uniformly distributed in it That this actu takes place, we demonstrate in the following way —

93 A long cylindrical jar is filled with water and st on a steady table By means of a funnel (*e g* thi funnel, see Appendix A) a strong solution of a colou salt, *e g* bichromate of potassium is poured into the ve so as to form a distinct layer at the bottom A white pa millimetre scale is fixed behind the vessel and a daily rec taken of the height reached by the potassium bichrom

This way of measuring the rate of diffusion is open the objections that changes of temperature set up c vection currents in the liquid, and that, unless the t on which the vessel stands is perfectly steady, vibrat caused by people walking in the room, etc , increases rate at which the liquids mix Both sources of error l to a fictitiously high result

The following method is simpler to carry out and is open to these objections —

94 To leaf gelatine, obtainable in commerce, enough water to form a liquid which, when it cools, to a firm jelly Before the liquid gelatine cools, ad

small quantity of thymol or other antiseptic (Appendix A), and also a few drops of phenolphthalein (Appendix A), a substance which undergoes a marked colour change—from colourless to rose—when acted on by an alkali. Pour the warm, liquid gelatine carefully into a tall jar and, when it has set, invert the jar over a dish containing a fairly strong solution of potash (KOH) or soda

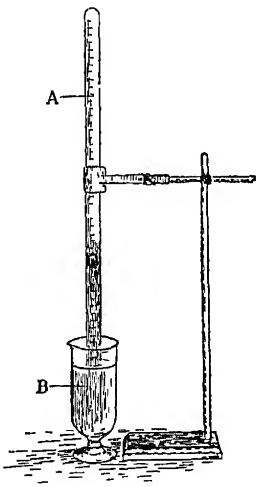

FIG 21.—APPARATUS TO ILLUSTRATE DIFFUSION OF LIQUIDS

A graduated glass tube [illegible] and an indicator (phenolphthalein) is inverted in a vessel (B) [illegible]

(NaOH), which give a strong alkaline reaction. Determine the rate of diffusion of the alkali by tracing the ascent of the rose colour. Record the results. The fact that the experiment lasts for weeks should not lead to neglect in the matter of recording, for it is important for us to learn that this liquid diffusion is a *slow* process. The experiment demonstrates also that the gelatine does not prevent the diffusion of water and potash.

We know from previous experiments (*e.g.* Exp. 26) that a similar intermixing of water and sugar takes

place when these substances are separated from
another by a parchment membrane Nor is this
prising if we suppose that diffusion of gases or
liquids is due to molecular- and not to mass-movemer
Although such a parchment membrane, when used to c
tain water, does not leak, its substance must be pictured
riddled with a system of ultramicroscopic spaces, too sn
to allow the smallest drop of water to pass, but am
large enough to allow of free movement of molecules
H_2O Inasmuch as the molecules of fluids are, accord
to our assumption, like those of gases, in constant mo
ment, some water-molecules pass into the interstices
the membrane, and, arriving at the other side, co
in chemical contact with the sugar-molecules The f
that sugar is soluble in water means that sugar- and wat
molecules exercise some attraction on one another
may conceive of the sugar-molecule linking with the wat
molecule and joining it in the molecular dance ; thou
being heavy, the sugar-molecule will cause a slowing
the rate of movement The molecular dance is cra
Sugar and water partners career in all directions, so
back through the interstices of the parchment membra
some on through the sugar solution Since the molecu
movements are unending, the result is that, in cou
of time, there are as many sugar-molecules per unit
volume on one side of the membrane as on the oth
Looking at the final result, we say that sugar and wa
have passed by osmosis each from one side of the me
brane to the other Even after equilibrium has be
reached, that is, when the liquid on one side of the me
brane contains per unit volume as much sugar as that
the other side, the molecular movements do not cea
But, in these circumstances, the number of sugar-molecu
conveyed in a given time across the membrane in
direction is equal to the number which pass in the oppos
direction Just so may the population of a town rem
remarkably constant though the townsmen come and g

In order to study the phenomenon of osmosis mo
closely, with the object of learning more about the me
of absorption by the plant, we make an osmotic appara
thus —

95 Cut off a length of about eight inches of parchment tube (Appendix B) If dry, soak the parchment tube in water when thoroughly wet, fix in one end a rubber cork without holes and make the joint good by winding tightly round the parchment tube many turns of stout silk thread or florist's buttonhole wire Stand the tube upright, open end uppermost, in a pail or other suitable large vessel Make two holes in opposite sides of the parchment on a level with the rim of the pail Pass a glass rod through the holes, and let the rod rest on the rim (Fig 11). Fill the outer vessel with water up to about two inches below the level of the glass rod, then fill the parchment tube nearly up to the level of the holes through which the glass rod passes Leave the apparatus for a short time and observe whether any water has escaped from the tube If so, there is a hole in it, and the tube must be replaced by another If it proves to be sound, empty the tube and cut away the part pierced by the holes through which the glass rod passed Choose a two-holed rubber cork which just fits the tube Insert through one hole the tubular limb of a separating funnel, seeing that it makes a good joint Through the second hole in the cork, pass a glass tube about three feet long so that its lower end is flush with the lower surface of the cork Stand the empty parchment tube in the vessel of water, insert the cork, and make good the junction between cork and tube by many turns of silk thread, supplemented, if necessary, by wax (Appendix A) Fix the glass tubes, or the longer one only, in a clamp, so that the lower cork rests on the bottom of the outer vessel and the parchment tube is steadied (Fig 22) Prepare a strong solution of sugar colour the sugar with a dye such as methylene blue Pour the coloured sugar solution into the separating funnel Open the stop-cock of the latter and run in the sugar solution till, the parchment tube being full, the liquid rises in the long glass tube to about half an inch above the level of the cork Close the stop-cock of the separating funnel Pour water into the outer vessel to about the level of the top of the parchment tube If any sugar solution has been spilled into the outer vessel, transfer the osmotic apparatus bodily to another, similar vessel of clean water

The apparatus is laborious to make, but is so instruc in action that no trouble should be spared to get it set An improvement which enables us to use it again and ag is illustrated in Fig 22 The outer vessel, which ser

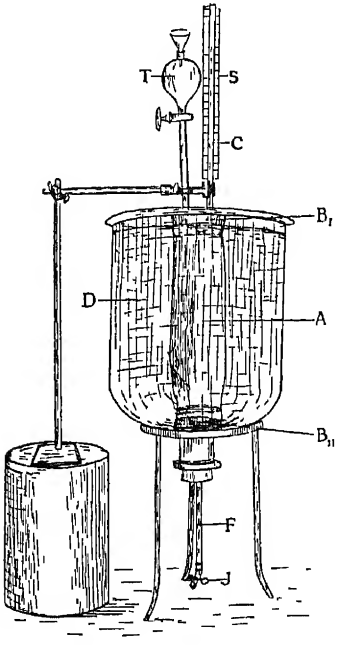

FIG 22 —APPARATUS TO DEMONSTRATE OSMOTIC PRESSURE

A, parchment tube, B_I, B_{II}, rubber corks, T, thistle funnel, C, glass tu D, vessel containing water, F, exit tube, J, clamp, S, scale

to contain the parchment tube, consists of an inver bell-jar with an open neck (Fig 22 D), and is suppor on a strong iron tripod-stand The lower end of parchment tube is closed by a rubber cork (B_{II}) with hole, into which is fitted a short glass tube, the upper of which is flush with the upper surface of the cork tube is passed also through the hole in a rubber cork wi

closes the neck of the bell-jar. To the free end of the short glass tube (F), a short piece of rubber tubing is attached and closed by means of a clamp (J). When the upper cork (B_1) with its funnel and long glass tube has been inserted in the upper end of the parchment tube, the bell-jar is filled with water and the apparatus is ready for use. The coloured sugar solution, to which a trace of an antiseptic may be added, is poured through the funnel and the air contained in the short tube F is expelled by opening the clamp J. After the apparatus has been used in the way about to be described, the liquid in the parchment tube may be withdrawn through the tube F and the parchment tube refilled with sugar or other solution, the osmotic properties of which it is required to test.

An osmotic apparatus of this kind, once fitted up, will last for months if the parchment tube is not allowed to become dry, and may be used for various interesting experiments in osmosis.

If all the joints are good and the parchment tube intact, the fluid begins to rise almost at once in the long glass tube. Fix a paper scale behind the long tube and take time-records of the height to which the liquid rises. After some time, it becomes necessary to add another length of glass tubing, which is connected with the long tube by a short piece of rubber tubing and supported, e.g. against the wall of the room. The liquid continues to rise to a height of many feet. Then, after some time, it begins to fall and finally descends to the level of the liquid in the outer vessel. Before this takes place, note that the dye has escaped through the parchment-wall into the water outside, and prove by the sugar test (Exp. 21) that sugar also has passed into the outer vessel.

The rise of the water in the long glass tube means that the volume of liquid in the osmotic apparatus has increased, and hence that water has passed through the parchment-wall. Therefore, in the course of osmosis there is, as indeed we should expect from our previous studies, a movement in both directions: sugar and soluble pigment pass from parchment tube to the outer vessel, water passes into the parchment tube. Since, moreover, the liquid rises in the long tube, the amount of water which passes in is greater

than the amount of sugar which passes out We may that the sugar solution exercises an osmotic attraction water, and that it sets up an osmotic pressure sufficien hold up the high column of water in the long tube

But since, from the moment the apparatus is set to we sugar begins to diffuse out into the surrounding liq and since, in that situation, it sets up a counter-attracti tending to withdraw water from the parchment tube, apparatus is useless as an osmometer,—that is, a measurer of the actual osmotic pressure exerted by original sugar solution It serves only to indicate t such pressure exists and can be made to do work, e g lifting water That the sugar which escapes into the ou vessel does set up a pressure tending to neutralise tha the parchment tube we demonstrate thus —When liquid in the long tube has reached a certain height has become fairly stationary, siphon off that in the ou vessel and replace it by water Note that the liquic the long tube begins again to ascend The level previou reached represented the resultant of the osmotic pressu exerted by the sugar solutions inside and outside parchment tube by removing the sugar from the ou vessel, the pressure exerted by that in the tube is no lon in part counteracted, and so is able to hold up a lon column of water

96 By using solutions, e g of cane-sugar and grape-sugar successively, we may demonstrate by me of our osmotic apparatus that the rates at which s stances in solution pass through a parchment membr depend, among other things, on their molecular weig The molecular weight of cane-sugar ($C_{12}H_{22}O_{11}$) is , that of glucose ($C_6H_{12}O_6$) is 180, therefore, if we diss the molecular weights of cane-sugar and of glucos grams, i e 342 grams of cane-sugar and 180 grams of cose in equal volumes of water, say 1000 c c , and use the one and then the other solution in the parchment t we find that the height of the water column supporte the cane-sugar solution is greater than that supported by grape-sugar For the heavier cane-sugar molecules dif more slowly than the lighter molecules of glucose He before the latter has had time to get up its full osn

pressure, much of it has diffused into the outer vessel Similarly if we fill the osmotic apparatus with a solution of potassium nitrate of corresponding strength, *i e* one containing the molecular weight of KNO_3 in grams, viz 101 grams, per 1000 c c of water, we find that, owing to the high rate of diffusion of potassium nitrate, the osmotic pressure which the solution sets up is very small indeed and by no means a true measure of that which it can exert

We have, however, in plant-cells and tissues an apparatus ready-made for comparing the osmotic pressures exerted by different substances For a vegetable cell is an osmotic apparatus strikingly similar to that used in Exp 95 The osmotic substances dissolved in the cell-sap correspond to the sugar or other solution in that apparatus, and the protoplasmic membrane (plasmatic membrane) of the cell corresponds to the parchment membrane If a completely turgid vegetable cell is placed in water, it undergoes no change in volume since the cell-wall is already stretched to its limit by the pressure of the cell-sap if, however, the cell is not completely turgid, water is absorbed, and the volume of the cell is increased—the osmotic pressure being used to do the work of stretching the plasmatic membrane and cell-wall If such a cell is placed in a strong salt solution, the osmotic pressure of the latter causes water to pass out from the vacuole, across the protoplast and cell-wall The amount of fluid in the vacuole being thus reduced, the pressure on protoplast and cell-wall falls off and the volume of the cell decreases As water is withdrawn, the solution of osmotic substances in the cell-sap becomes more concentrated, and consequently the osmotic pressure of the cell-sap increases If the osmotic pressure of the salt solution used is greater than that of the concentrated sap, more water is withdrawn from the vacuole, plasmolysis sets in, and, yet more water being withdrawn, the protoplast, shrunk away from the wall, may collapse and become disorganised If, then, we place vegetable cells or tissues in salt solutions of different strengths, we find that, whereas, in strong solutions, plasmolysis is complete, and in very weak solutions it does not occur at all, there is one strength of solution which just suffices to produce the early stage of plasmolysis and no more

NO_3, and if each of these exercises osmotic pressure, we can form an idea of the reason why the osmotic pressure exerted by a solution of KNO_3 of known strength is greater than we should have expected on the basis of the "law," which we have established for cane-sugar and glucose, that equi-molecular solutions of osmotic substances exert equal osmotic pressures It was by means of experiments such as these that the discovery was made that the osmotic pressure of a substance is a property of its molecules in the same way that weight, etc , are properties of the molecules These discoveries have led to others of equal interest, and those in turn have served as the basis for various theories to account for the known facts We cannot, however, pursue this part of our subject further, but refer students who wish to learn more about the physical aspect of osmotic pressure to the larger text-books (Bibliography, 11)

The comparison of a plant-cell with the osmotic apparatus of parchment tube (see p 113) fails in one very important particular For, whereas such substances as soluble pigments pass readily across the parchment-wall (see Exp 84*), the soluble pigment in the cell-sap remains, in the partially plasmolysed cell, enclosed within the plasmatic membrane There must, therefore, be an important difference between parchment and protoplasmic membranes The parchment membrane is indiscriminately permeable to diffusible substances, such as water, sugar, potassium nitrate, soluble pigments like methylene blue, etc , but the protoplasmic membrane is not The former kind of membrane is called a permeable membrane the latter kind, which is permeable to water but not to all diffusible substances, is called a semi-permeable membrane The importance to the plant of this property of semi-permeability is very great indeed for, were the osmotic membrane of the plant-cell permeable, there would be a constant osmotic leakage of osmotic substances from the cells of the plant into the soil just as there is a constant osmotic leakage of sugar from the osmotic apparatus of Exp 95

98 Instead of using cells with coloured cell-sap, the curved pieces of split dandelion stalk (Exp 91) may be

employed in the above experiment To use them, proceed as follows —

Split a dandelion stalk longitudinally into four pieces cut the pieces into lengths of about an inch each, and having prepared the series of solutions the osmotic pressures of which are to be determined, trace on paper, by means of a brush and india-ink, the amount of curvature of each piece of stalk Throw a piece into each of the solutions, after some minutes, take the pieces out, determine which have curved more, and which have become straighter

The solutions which have caused a straightening have done so by withdrawing water from the cells of the dandelion Their osmotic pressures are, therefore, greater than the osmotic pressure of the cell-sap of the cells of the stalk Those solutions in which the pieces have curved more have yielded water to the cells, that is, the osmotic pressure of these solutions is lower than that of the cell-sap of the dandelion cells Hence, by finding a solution in which pieces of dandelion stalk retain their curvature unchanged we find what strength of solution is in osmotic balance with the cell-sap

99 By using pieces of dandelion stalk in the same way we may compare known strengths of different osmotic substances with one another, with respect to their osmotic pressure

It is important to demonstrate that the property of semi-permeability referred to on p 115 is not confined to living membranes

100 Thus we may make a semi-permeable membrane called, because of its mode of preparation, a precipitation membrane, by causing solutions of copper sulphate and potassium ferrocyanide to interact The precipitate of copper ferrocyanide which forms as the result of this interaction, is not granular, but skin-like To prepare it, pour a 3% solution of potassium ferrocyanide into a wide mouthed bottle fitted loosely with a cork Fix a glass tube, drawn out at one end to a fine point, in a hole in the cork so that its fine end dips below the ferrocyanide solution Having withdrawn and cleaned the tube, draw a drop of strong copper sulphate solution into it, close the tube

by the finger, and fit the cork attached to it in the neck of the bottle so that the fine end of the tube is just below the surface of the potassium ferrocyanide solution When the finger is removed from the end of the tube, the copper sulphate reacts with the ferrocyanide to produce a membrane, which closes the fine end of the tube Inasmuch as the copper sulphate on one side is a strong solution and has an osmotic pressure higher than that of the weak potassium ferrocyanide solution on the other side of the precipitation membrane, water passes from the latter solution to the former Hence the volume of the copper sulphate solution increases, its increased weight stretches the precipitation membrane and the "artificial cell" grows As the pressure of the copper sulphate solution increases further, the membrane is ruptured, but it forms again owing to a new skin of copper ferrocyanide being produced as soon as the copper sulphate and potassium ferrocyanide come in contact Again the "cell" grows, and again it is ruptured to be once more repaired This membrane, permeable to water but not to such substances as copper sulphate or potassium ferrocyanide, is a semi-permeable membrane

Another method of making a semi-permeable precipitation membrane is as follows —

101. To ordinary gum, add a small quantity of gelatine, some sugar and a little colouring matter, *e g* aniline blue in solution Take up a little of the gum-mixture on the rounded end of a piece of thick glass rod and expose it to the air till it is dry Put the rod so that its gummed end is in a 2% solution of tannin A membranous precipitate of tannate of gelatine is formed on the surface of the dried gum The sugar contained in the gum exerts its osmotic pressure, water passes across the membrane, the latter is stretched and behaves like the membrane in the former experiment The dye, however, does not pass across Thus the precipitation membrane behaves like the plasmatic membrane of a vegetable cell (cf Exp 84*), permitting water to pass across, but preventing the osmosis of the dissolved pigment

102 Again, we may illustrate the semi-permeability of precipitation membranes by the use of our parchment tubes.

Prepare two tubes, A and B, supported by glass rods a
Exp 17 Into each pour a 1 % solution of calcium nitra
stand A in water and B in a 1 % solution of disodic ph
phate Add a little methylene blue to the liquid in e
parchment tube After a day, note that the methylene l
has appeared in the water of the outer vessel of A,
not in that of B In B, the calcium nitrate and disc
phosphate interact to form a precipitation membrane
calcium phosphate on the wall of the parchment tube,
this membrane, though permeable to water, is impermea
to a solution of methylene blue

On the lines of such an apparatus as that of Exp 1
a perfect, working, osmotic model of a vegetable cell r
be constructed

Thus we reach the end of our enquiry We disco
that, by means of its root-hair cells, the root absc
water together with any soluble osmotic substances
which the plasmatic membrane of the root-hair cell
permeable What these latter substances are, we n
determine by other methods and in another chapter

CHAPTER VIII

THE substances taken up by the roots of plants The composition of plant ash Water- and sand cultures The soil in relation to plant life The origin of soils their physical, chemical, and biological properties

THE fact, established in the last chapter, that root-hairs are capable of absorbing water and any other soluble substances to which their plasmatic membranes are permeable, leads directly to the enquiry —What are the substances which the roots of plants absorb, and to what use does the plant put the substances which it obtains from the soil?

That water is absorbed by the root is evident without further experiment, for, on the one hand, we have found (Exp 5) that plants contain large quantities of water, and, on the other, we know that unless water is supplied to their roots, plants wither and die

Presently we shall have to enquire more closely into the relation of the plant to water, but, in the meantime, we will devote ourselves to discovering what substances, other than water, are absorbed by the root

The same experiment which taught us that the tissues of plants contain considerable quantities of water, proved also that the dry matter, left after the water is driven off, consists largely of carbon compounds, and that, after these compounds are burned away, a relatively small amount of mineral matter remains behind as ash

Now, carbon compounds of the kind contained in the plant do not exist in the soil, but inasmuch as such mineral substances as those found in the ash are always present in the earth, we may be fairly confident that the mineral substances of the ash of plants are obtained in one form or another from the soil

To determine accurately and completely all the con-

stituent elements contained in plant-ash would require a somewhat elaborate chemical analysis Though such an analysis is beyond us, we can demonstrate readily the presence of some of the more important elements by the following methods —

103 Fill a large bottle with fine ashes from a bonfire, or from a bundle of dried hay burned for the purpose

Place some of the ash on a piece of platinum foil (Appendix A), and heat it in a Bunsen flame Roll up the platinum foil with the remains of the fused ash, place it in a test tube, add a little distilled water boil Test the solution so obtained with red litmus paper a blue colour shows that an alkali is present (Use the solution for Exp 105)

104 Moisten a platinum wire (Appendix A) with hydrochloric acid, dip it in the ash and hold it in the flame Observe the yellow colour of the flame, due to the presence of *sodium* Repeat, observing the colour of the flame through a piece of cobalt-blue glass a violet colour indicates the presence of *potassium*

105. To the solution obtained in Exp 103, add an equal volume of dilute nitric acid Pour the liquid into a clean test tube, add an excess of a solution of ammonium molybdate (Appendix A), boil a yellow precipitate indicates that *phosphates* are present in the ash

By appropriate tests, the presence in the ash of other mineral substances—compounds of *calcium, magnesium,* etc —may be demonstrated

It is to be noted, however, that these tests give no indication as to the form in which the elements, potassium, magnesium, calcium, etc , exist in the plant, for the compounds present in the intact plant are decomposed in the process of burning.

Since, however, as our tests indicate, potassium, sodium, calcium, phosphorus, etc , are present in combined form in the ash, these elements must have been present in some form or other in the plants which yielded the ash Whence it follows that they were obtained from the soil

The question therefore arises, are the mineral substances which plants contain mere accidental accumulations or are they of significance in plant nutrition?

that silicon, chlorine and sodium, though generally pres in plant-ash, are not essential for the perfect developm of flowering plants in general

Since water- and sand-cultures are among the m instructive experiments in plant physiology, we proc to carry them out with a view to ascertaining what sy toms are manifested by plants deprived of one or othe the essential, mineral substances The salts and also water used for the culture solutions must be pure full instructions as to the mode of preparation of solutions, see Appendix A

It will be of interest to repeat, as the first of our sa culture experiments, the original sand-culture made Boussingault, who introduced the method about 1868

106 Procure good silver sand, clean it (Appendix place pieces of clean crock (broken flower pots) at bottom of each of six, small, new pots and fill the pots v the sand plant one pea seed in each pot (the seeds, be planting, may be plunged whilst dry into hot water a few minutes, soaked in tepid water for twelve ho and then sown) Water thoroughly and cover the p each with a piece of glass When the seedlings app water three of the pots with complete culture solu (Normal solution, Appendix A), and three with a cul solution complete, except for nitrates (Normal, m nitrates) When planting the seeds in the pots of s plant others in pots of ordinary soil to serve for c parison Record the rate of growth of the seedli of the three series when the difference between th with and without nitrates has become marked, draw photograph the plants (Frontispiece) From the starve appearance presented by the plants grown in sand lacl nitrates, and from the healthy appearance presented those in sand containing nitrates, we conclude that a p cannot live without nitrogen, that the supply of nitr which the seedling peas contain in the form of prot in the aleurone grains of the cotyledons (cf Chapter is soon exhausted, and that the plant then turns the soil for further supplies of nitrogen, which supp the soil may furnish in the forms of nitrates Be thus demonstrating that plants derive nitrogen from

soil, we get a striking example of the complexity of the chemical process carried on by plants For, from our study of the nutrition of seedlings, we have learned that plants build up their protoplasm from complex, organic nitrogen-compounds (*e g* proteins), and now we are driven to the conclusion that the raw materials, which provide the nitrogen contained in the proteins of plants, are the relatively simple, inorganic nitrogen salts which are absorbed from the soil Though physiologists have spent much time in investigating the process of nitrogen-assimilation, *i e* the process whereby the nitrogen of the nitrates of the soil is combined with other elements to form amino-compounds and proteins, our knowledge of the subject remains fragmentary (Bibliography, 10, 11)

Beside its historical interest, this sand-culture experiment of Boussingault has yet another interest, and for that reason we shall return to it presently (p 141)

107 Repeat Exp 106, using plants with smaller seeds in order to avoid the complications introduced by reserve-materials Among the various plants which may be used successfully for sand-cultures, poppies (Papaver sp) or the Californian poppy (Eschscholtzia californica) are, by reason of the readiness with which they grow in sand, among the best

108 By means of sand-cultures determine the effect of withholding certain of the other elements of our list, viz :— calcium, magnesium, and phosphorus (see Appendix A) Though the results are less striking than those obtained by withholding nitrogen, yet, in each of these cases, the plant fails to develope properly

Mount the drawings or photographic records of the sand-culture experiments on cards add details and preserve them in the museum Record peculiarities as to leaf-development, colour of leaves, growth of stem, flower- and fruit-formation in each case

Unless the sand used in the above cultures is pure, and unless special precautions are taken, an attempt to demonstrate the effect of withholding iron will fail, and this for two reasons First, the amount of iron required by plants is extremely small, and second, traces of iron occur in most samples of sand Hence to demonstrate the effect

produced in the plant by lack of iron we resort to t
method of water-culture (Appendix V)

109 Procure several good-sized glass bottles—la
jam bottles answer the purpose well Clean and
them and immerse the bottles almost to their rims in l
water of a temperature of about 50° C Melt a little so
paraffin (of melting point 40° C , see Appendix V)
a porcelain dish, and pour it into one of the bottl
Rotate the bottle so that the paraffin, as it cools, for
a thin layer over the whole of its inner surface Tr
the other bottles in a similar way Having germinat
maize so that the roots of the seedlings are in wat
remove the endosperm from each of several seedling
replace the seedlings and leave them for a day with th
roots in water Fill two paraffined bottles, one w
"normal" culture solution the other with "normal, min
iron" Make several cuts in a plate of cork, passing fr
the edge to near the centre Slip the lower parts of t
shoots of healthy seedlings each into one of the groove-l
cuts, wedge each seedling firmly by means of cotton wo
place the cork over the bottle, the fluid in which is at su
a level that it covers the roots but does not reach the shoo
By adopting the precautions mentioned in the appendix, t
plants may be kept in a healthy state Note that t
leaves which form in the "normal, minus iron" soluti
are not green but yellowish or white In the abser
of iron, chlorophyll, the green colouring matter of plan
fails to develope Paint a part of such a chlorotic l
with a dilute solution of iron sulphate, and observe th
it becomes green in the course of a day or so

It is a curious fact that though iron is essential for t
development of chlorophyll, that substance does not cont
iron

In Nature, certain plants on certain soils become chloro
and fail to develope properly It has been shown that t
state is due—at all events in many cases—to the inability
the plants to obtain iron from the soil, and that it m
be remedied by injecting solutions of iron salts into t
stems It must be borne in mind, however, that not
white leaves are due to the lack of iron Many plants, e
maple, ivy, holly, pelargonium, etc , have the habit

forming races with variegated leaves, and, in these cases, we have no reason to think that the absence of colour is due to lack of iron: again, most plants grown in darkness (cf p 44) produce colourless leaves Hence we may suppose that the presence of iron salts, like light, is a necessary condition for the development of chlorophyll

By referring to the records made of the growth of the sand-cultures, it will be found that, when calcium is absent, the leaves tend to become yellowish, and that, in the absence of magnesium, they often take on a dirty-brown colour. Inasmuch as it has been shown recently that chlorophyll contains magnesium, it should be possible to demonstrate that, in the complete absence of that element, plants do not produce the normal green chloroplasts (chlorophyll grains)

The results of sand- and water-culture experiments prove that the following elements obtained in combination from the soil in the form of salts are essential for the growth and development of flowering plants —nitrogen, phosphorus, sulphur, calcium, magnesium, potassium and iron, together with hydrogen and oxygen obtained in the form of water (H_2O) As the result of chemical processes, of which at present the green plant guards the secret, certain of these elements—nitrogen, sulphur, phosphorus, and potash, as well as oxygen and hydrogen—become constituents of plastic food-materials such as the proteins, and, finally, are incorporated with the protoplasm Others, such as magnesium, become part of the indispensable chlorophyll grains Hence we must regard the essential mineral salts as contributing with water to the raw materials of the food

The precise function of some of these mineral substances is not clear Some of them, as, for example, iron, seem to condition the formation rather than to enter into the construction of the plant-machinery, others play yet other parts—thus calcium has a rôle in connection with the transport of plastic carbohydrates For, in its absence, the accumulation of starch in abnormally large quantities in the leaves, indicates that something has gone wrong with the transport service (cf also p 185) Calcium occurs also in a combined form in certain layers of the cell-walls

Our studies of the osmotic properties of cells h taught us that only such mineral substances as are solu in water can pass into the root-hair cell That the r has, however, the power of dissolving certain mine substances, we demonstrate thus —

110 Pack a large flower-pot half full with coco-fib place a slab of polished marble so that one end rests the coco-fibre and the other on the side of the pot, such a position that downward-growing roots come contact with the surface of the marble Press a layer coco-fibre firmly into the pot, plant soaked bean seeds, co them with coco-fibre, and water thoroughly After se weeks, turn the marble out of the pot and observe that root-systems of the seedlings have etched upon the s copies of their outlines Since marble ($CaCO_3$) is solu in water containing carbon dioxide (CO_2) in solution would suffice for the etching process for the root to p duce—as we know it does—carbon dioxide Whether root-hairs are able also to excrete other more powerf solvent substances is a matter of dispute

That the mineral substances absorbed by the root-h are taken up in extremely dilute solution follows from diluteness of the solutions which suffice for water-sand-cultures Indeed, our study of osmosis would l us to predict that, where the rooting medium cont osmotic substances in any considerable degree of conc tration, water absorption is hindered (cf also p 128)

We demonstrate the fact that the addition of str solutions of salts may act injuriously on plants, e g plasmolysing the root-hairs, thus —

111 Raise turnips or oats from seed planted in six p of ordinary soil When the seedlings are up, water one the pots daily with one of the following —water, 1%, 5%, 10% and 20% potassium nitrate solutions, and de mine that the strong solutions exercise a disastrous eff

Gardeners have long since recognised the fact that a may be deficient in some one or other of the essen mineral substances required by plants, and that, e though it may not have lacked such a substance origin it may come to be poor in an essential mineral, owing the absorption of this substance by previous crops T

know, also, that animal manures contain relatively small quantities of such substances as phosphates Hence, in order to restore the fertility of the soil, they apply to it both dung and artificial manures or fertilisers When a fertiliser is readily soluble in water, *e g* nitrate of soda, sulphate of ammonia, etc , care is taken to add it in small quantities, for, otherwise, it is apt to "burn" the plants

112 This burning effect may be demonstrated by adding powdered sulphate of ammonia to a patch of a lawn infested with daisies After a few days, the daisies present on the lawn are brown and shrivelled, and the grass itself may be also damaged temporarily It is owing to the special susceptibility of daisies to damage by sulphate of ammonia that this substance is employed, mixed with sand, as a weed-killer on putting-greens and lawns

Another matter of interest which our various observations now allow us to explain, at all events in part, is that known as *selective absorption* Different crops make different demands on the mineral constituents of a soil Some, like potatoes and root-crops generally, take up more potash salts, others, like leguminous crops, take up more phosphates, and so on Now, if a substance, say a salt of phosphorus, is taken up by the root and distributed throughout the plant, a moment comes when, if the phosphates in the plant have not in the meantime undergone some change, there is as much phosphate in solution in the cell-sap as in the water of the soil Hence, automatically, the accumulation of phosphates ceases If, then, we consider two plants, one which makes use of phosphates largely, the other sparingly, then, though grown in precisely similar soils, the former takes up during its life large quantities of phosphates, the other takes up but little It will be evident that the behaviour of different crops with respect to amount of absorption from the soil of the essential mineral substances must be a factor in determining the rotation of crops

It remains to enquire how the dilute solutions of the various mineral substances are absorbed by the root We have described the plasmatic membrane of the root-hair as a semi-permeable membrane, that is, one which, whilst

permeable to water and certain diffusible substances, impermeable to certain other diffusible substances We have, therefore, to assume that the root-hair cell, while impermeable to the osmotic substances which it contains dissolved in the cell-sap of its vacuole, is, on the other hand, permeable to nitrates, and to the salts of the other elements essential to plants On this view we can understand how certain plants take up large quantities of non-essential minerals—just as sea-weed absorb large quantities of salts of iodine We suppose that large differences of permeability exist, and that the protoplasmic membrane of the root-hair cell of one plant is permeable to substances which cannot pass the plasmatic membrane of the root-hair cells of other plants

The study of the behaviour of a plant, the absorbent organs of which find themselves confronted with new osmotic conditions, throws light both on the extent and limitations of the plant's powers of adaptation Thus, the roots of willows grow in the strongly saline waters of the Dead Sea, and hence the root-hair cells, immersed in the salt water, the osmotic pressure of which is very high must exert a correspondingly high osmotic pressure order to retain their turgidity and to effect the absorption of water Some marine algae withstand a change from salt water to fresh water, a change which would suffice to produce death from "osmotic explosion" the cells of most plants Brought into solutions higher osmotic pressure, the absorbent cells of some plants react by setting up a countervailing osmotic pressure by the secretion of osmotic substances into the cell-sap oth plants reach a similar condition of osmotic equilibrium with the fluid which surrounds them by absorbing osmotic substances from it On the other hand, plants are not always able to readjust themselves so as to overcome untoward soil-conditions Thus, a certain number of plants are very intolerant of chalky soils Among such chalk-shy calciphobe plants are sphagnum moss, the sun-dew (Drosera rotundifolia), and other plants common in boggy and peat land, foxgloves (Digitalis purpurea), rhododendron azaleas, etc The leaves of azaleas and rhododendron

grown in soil rich in chalk, turn a sickly yellow colour, whilst the sun-dew and various mosses may be killed outright. It seems probable that though, for some reason or other, an excess of lime is injurious to these plants, their root-hairs are, nevertheless, permeable to soluble salts of lime, and have no power of modifying this property. In the cultivation of azaleas and other chalk-shy plants in greenhouses, gardeners are careful to water them with soft water, and advantage is taken of the susceptibility of various mosses to lime to get rid of them from lawns by watering with lime-water or by dressing the lawns with chalk.

Other plants are indifferent to chalk, and yet others (calciphil plants) show a marked preference for chalky soil (Bibliography, 1, 9, 17). Hence, in the cultivation of alpine plants from limestone regions, it is sometimes necessary to use stone containing lime for the construction of rock-gardens.

Our sand- and water-cultures have convinced us of the fundamental importance of the soil to the life of the plant. From it, the plant derives not only its water supplies, but also the mineral substances indispensable to its existence.

In addition to these fundamental relations between plant and soil, there are others hardly less striking, for even in the course of a walk across a small tract of country, it may be seen that the different kinds of plants are not scattered uniformly over it, but group themselves into bands, and that the kinds or types of vegetation characteristic of these several plant-associations are very different from one another (Bibliography, 1, 9).

Over that small tract of country the climate is uniform, throughout it the amounts of rainfall and sunshine are about the same. Therefore, we are compelled to conclude that the differences in vegetation which its several parts present are due, in some way or other, to differences in the soil.

The same conclusion is reached from a survey of the vegetation of the whole world. Woodland and grassland occur the world over, alike in the hot regions near the equator, and in the cool temperate regions. The fact that the species of plants which compose a tropical

jungle differ from those which live in an English wood is to be attributed mainly to differences of temperature. Only plants that can withstand a fairly low temperature survive in an English wood, and only plants that can flourish at a uniformly high temperature live in the tropical jungle. But the *tree-type* of vegetation is common to both, and the existence of this type in such different regions is to be attributed to similarity of soil conditions, particularly, as we might guess, to there being a supply of water adequate for the support of luxuriant tree-growth. Thus, the question of the plant's water-supply is one which has many bearings, and is worth careful consideration. That this supply depends ultimately on amount of rainfall—or, in some cases, on supplies of underground water—is evident; though it is also evident, from the facts we have learned (p. 128), that plenty of water in the soil need not necessarily mean plenty of water available for the plant.

Consider, for example, how the vegetation of the land comes in our country to a sudden halt at the sea-shore. None of the plants that flourish a few yards inland are able to establish themselves on the sandy beach. That strip of ground is practically a desert, or at best bears occasional, isolated plants, such as sand-binding grasses (Ammophila arundinacea), yellow horned poppies (Glaucium luteum), sea thistles (Eryngium maritimum), and sea convolvulus (Convolvulus Soldanella). Nor is the dearth of plants along the sea-shore confined to the sandy tracks. In the wet, clayey marshes which mark the estuaries of small streams, the vegetation, consisting of sedges, succulent Suædas and Salicornias (Marsh Samphire, Saltwort), is but poor. Over these marshes, the sea spreads at periods of highest tides, and few plants can live in the soil impregnated with sea salts. Thus, within the space of a few hundred square yards three different types of vegetation may occur, the grassland or woodland, which comes almost to the sea's edge, the semi-desert of the sandy shore, and the salt-marsh. The reason for this grouping of plants according to soil characters is not far to seek. For sandy soils are leaky reservoirs, from them the water drains away almost as fast as it falls as rain upon them. In the salt-marsh also, the cast-

ing vote which determines vegetation is given by the soil, for only plants (halophytes) whose roots are tolerant of large quantities of salt can live therein

Hence a region of uniform rainfall may contain soils which, like those of the meadows or woodlands by the sea, are good water-reservoirs, others which, like the sandy shores, are poor reservoirs—physically dry—and others, like the salt-marshes, which, though they hold much water, withhold it from the majority of plants, and are therefore, though they may contain plenty of water, dry as far as plants are concerned, or, as we say, physiologically dry. Such brief considerations show that a study of the soil is a matter of first importance to the physiologist. To this study—of the physics, chemistry, and biology of the soil—we will now proceed.

Soil is "rotted rock." By the action of rain and running water, frost and other natural agents of destruction, the rocks exposed on the surface of the earth are in part dissolved and carried to the sea by rivers, and in part broken into the fragments of varying size which constitute the soil.

The soil thus formed may accumulate over the rock from which it is derived, or it may be carried by running water for some distance and then be deposited. In the former case, the soil is called a sedentary soil, and in the latter, a transported or drift soil.

Since different rocks are composed of different kinds of minerals, they give rise to soils which differ chemically from one another.

Thus, a limestone disintegrates to form a chalky soil. Rocks rich in felspar (silicate of alumina with potash, soda, or lime) give rise to a clay—a soil consisting mainly of fine particles of hydrated silicate of alumina. If much lime occurs mixed with clay, the soil is termed a marl. From rocks made up chiefly of quartz (silica) the coarse-grained soils, called sandy soils, are formed. Mixtures of sand and clay, in which the decaying remains of plants and animals (humus) have accumulated, are called loams, and constitute the most fertile soils.

The rarer minerals contained in the rocks scarcely affect the general character of the soil, though some are, as we

know, by no means unimportant to the plant. Of t
mineral substances, iron in combination is present in
soils in sufficient quantities to give rise to characte
colours red, yellow, blue, or grey which may be
pronounced as to be recognizable even in soils wh
owing to the humus they contain, tend to be of a blac
hue.

Fuller information as to the origin of soils may
obtained from text-books of Geology (Bibliography,
13, 17), and much may be learned concerning the or
and nature of the soils of a locality by studying them
the aid of the "drift maps" published by the Geolo
Survey.

113 For our first experiment in connection with
study of the soil, we dig a large hole in a field or gar
As the earth is turned up and put on one side, not
depth and also the change of colour as soil merges
subsoil.

Press a little of the soil between the fingers and
whether it feels gritty or greasy. If gritty, we know
it is of a sandy nature, if greasy, that it is clayey.

114 Heat a small quantity of the soil to redness
porcelain crucible. When it has cooled, note that, d
to the humus having been destroyed by burning, th
ignited soil has lost its blackish colour. Repeat
observations on the subsoil, and thus determine that
devoid of humus.

115 Half fill a test tube with a sample of the s
Add a little hydrochloric acid; note whether effervesc
occurs. If in doubt, hold the tube to the ear and liste
a crackling or bubbling sound. Effervescence indi
that the soil contains carbonate of lime, which, on
addition of the acid, disengages carbon dioxide.

116* Shake up samples of the soil with wate
tall glass jars or test tubes. Pour off the l
from one of the jars almost immediately, and from
other jars at timed intervals, leaving, however, on
undisturbed.

117.* By means of a long pipette, take out sampl
the sediment from each jar and examine it microscopi
Observe that the larger soil-particles fall first. Mo

drop of the turbid liquid contained in the last jar, look at it under the microscope and note the minuteness of the particles which it contains Ascertain how long the water in the undisturbed vessel takes to become clear

118 If several days elapse before this happens, pour half the contents into a clean vessel and add a little lime-water Observe that the effect of lime is to precipitate the fine particles, and note that lime is used in agriculture for the purpose of making clay soils more workable

119. Throw back the soil into the hole (Exp 113) without treading it down Note that the earth by no means completely fills the hole. Hence, even though put back with care, it is more tightly packed than before it was dug out, and hence, also, the particles, in their natural position in the soil, are separated from one another by spaces

120 Plunge a flower-pot, containing a plant not watered recently, in a pail of water: note that, as the water enters, bubbles of air escape from the spaces between the soil-particles

121 Take two similar plants in pots, *e g* geraniums, or chrysanthemums, submerge the pot containing one plant in water in a pail, grow the other plant in the usual way Note that the plant in the water-logged soil fails to flourish After some time, turn it out from its pot and observe that the roots appear unhealthy and, it may be, rotted Excess of water means deficiency of air, and hence an unsatisfactory rooting medium (see also Exp 67)

From the foregoing experiments and considerations, it is evident that a knowledge of the physical, as well as of the chemical, properties of soils is essential to an understanding of the relations which obtain between plant and soil

We will, therefore, devote ourselves to a brief experimental study of some of the more important physical properties of soils

122 For this purpose, obtain samples of fairly fine sand or of a sandy soil, and of a heavy clay

Having dried the soils in an oven, pound and sift them to remove stones, etc Without pressing down the particles, fill two pots of equal size and of known weight, *e g* marmalade jars or pint pots,—one with the sand, the other with the clay Determine the weights of

the equal volumes of sand and clay Note that sand is heavier than clay, and observe, therefore, that the farmer, when he speaks of a clay soil as 'heavy," means that it is heavy to work on account of its tenacious nature

Next compare the water-capacities of the two samples of soil, that is, the amount of water which can be taken up by an equal volume of each

123 To do this, fill a graduated burette with water, and run the water from the burette gradually into the vessels containing the sand and clay used in the last experiment As soon as the soils can absorb no more water, weigh the vessels, and remembering that 1 cubic centimetre of water weighs 1 gram, calculate, from the increased weight, the volume of water absorbed by the sand and clay respectively

Since both sand and clay consist of solid particles, the water added to the vessels has passed into the spaces between the soil particles, and thus the amounts of water taken up by the sand and clay give us a measure of the total volume of the spaces between the soil particles, or, in other words, of the pore-space of each soil

124 Turn the wet soil out of the pots, clean, dry, and fill them again with samples of dry, sifted soil—sand and clay as before Shake down the soil particles by tapping the vessels repeatedly against the table, observe that, as a result of such treatment of the dry soils, the clay particles lie closer to one another than do those of the sand, and that in consequence, the space now occupied by the clay is considerably less than that occupied by the sand

125 * Mount a small quantity of the sand in a drop of water on a glass slide, and make a similar preparation of the clay Examine microscopically, and observe that the sand particles are much larger than those of the clay (cf Exp 117*) Since a relatively large particle of sand is heavier than a minute particle of clay, sand particles lie more heavily on one another than smaller and lighter clay particles We thus recognise that the much larger pore-space of the clay soil (Exp 123) is due, not to the *chemical* properties of clay, but to the fact that it consists of minute particles which lie lightly on one another, and so leave considerable spaces between

Since they are so small individually, the number of clay particles in a given volume of clay soil is considerably greater than that of sand particles in an equal volume of sandy soil

Our experiments teach us further that, after a heavy rainfall over fields, some of which have a clay and others a sandy soil, assuming that the layers of soil are of equal thickness, more water is contained in the former than in the latter

But, as we know, the rain which falls on fields disappears gradually, and we must ask whether the "drying-up" proceeds more quickly in one kind of soil than in another

If we have at any time observed the sand on the seashore, we must have noticed that in summer, soon after the tide has receded, its surface becomes quite dry, whereas the clayey ooze lower down the beach remains for hours glistening with the water which remains on its surface Evidently, water does not drain away so quickly from a clayey as from a sandy soil

How marked is the difference between different kinds of soil in this respect we may demonstrate as follows —

126 Procure two *glazed* flower-pots of equal size, each with a hole in the bottom Close the holes by means of tight-fitting corks and determine the volume of each pot by measuring the amount of water required to fill it Remove the corks, dry the pots and place a small filter-paper in each to prevent the soil from escaping through the hole Fill loosely one pot with dry, sifted sand, the other with dry, sifted clay

Add water gradually as in Exp 123 until the soil is saturated and the pots can hold no more Cover each pot with a glass plate, stand it in a saucer or bowl, weigh, and record the weights Remove the pots from the saucers and stand them on blocks of wood or retort stands so that the water is free to drop from the holes Compare the rates at which the water drains away After some hours weigh the pots again and estimate the relative rates of percolation of the water

We learn thus that clay holds more water, and holds it more tenaciously, than sand Whence it follows that, since the water is held in the pore-spaces, a sandy soil

becomes dry more quickly than does a clay, and th
latter tends to become water-logged—and, owing to
of air, sour—more readily than does a sandy soil

The bearing of these facts on the drainage of agricu
land is evident

127 When water has ceased to drip from the two
of Exp 126, weigh them Knowing the total amou
water held by known volumes of similar samples of
and clay (Exp 123), and knowing the volumes o
glazed pots, calculate the amount of water held b
sandy and clayey soils respectively, after percolatio
ceased

128 Now remove the glass covers from the pots
placing the latter where they are sheltered from rain,
the soil exposed to the air By weighing at inte
ascertain that the sandy soil loses water by evapo
more quickly than the clay

In order to understand how this comes about, we
determine how the water is held in the soil after pe
tion has ceased We obtain an insight into the nat
the force by which the water is held on the surface o
soil particles by the following experiment

129 Take a series of capillary glass tubes, so
wider, and some of narrower bore the bore of the l
being about 1 mm, and that of the smallest about 2
Stand the tubes vertically so that their lower ends dip
water, which may be coloured with methylene blue or
dye Determine the height to which the water ri
the several tubes, and note that, the narrower the bor
higher the capillary rise Note also that the upper
surface of the water in the capillaries is not flat bu
curve, rising higher at the sides where it is in contac
the glass than in the middle, and observe that the nar
the capillary, the greater is the concavity of the surf
the water contained in it Since, to lift the water
tube, work must be done, it follows that the inner su
of the tubes exert a pull on the water, and tha
narrower the tube the greater the pull The force ho
up the water-columns is called surface-tension, an
water is said to rise in the tubes by capillarity Tub
narrow as to exhibit the phenomenon are called cap

tubes Now we have already discovered (Exp 123) that the soil is penetrated in all directions by exceedingly fine spaces, and since water, added to the surface, drains away below, it follows that these spaces form a system of intercommunicating channels With this conception of the soil, it is easy to understand how it is that after water has percolated from a soil the latter still contains a large amount of moisture We conceive of the water held by the soil as forming films of greater or less thickness around each particle, and of being held thus with considerable force If a soil consists of extremely fine particles, the number of particles per cubic inch is far larger than that in an equal volume of soil built up of coarse particles Hence the total surface of the particles of this volume of the fine soil is far greater than that of the particles of the coarse soil

In illustration, we may quote from Mr A D Hall's book on the soil (Bibliography, 16), the extent of the surface of the particles of a clay soil, a loam and a sandy soil —

Pore space %	Area of surface of soil particles in sq ft per cubic foot of soil
Fine clay soil - 48	110,500 square feet
Loam - - 44 1	46,000 ,, ,,
Sandy soil - 32 5	11,000 ,, ,,

From these numbers it is evident that the total surface presented by the particles of a clay soil is about ten times greater than that of the particles of an equal volume of sandy soil, and the number of water-films held tenaciously by surface-tension is, therefore, much greater in the case of the clay soil

This picture of water in the soil held in the form of films or hollow shells on the surfaces of the soil particles helps us also to imagine what happens as the soil dries by evaporation As the surface layer exposed to warm air or dry winds loses water in the form of vapour, the water lost is replaced by that attracted from the particles

below—for the thicker the film the less firmly it is held and conversely, the thinner the film the greater the surface-tension exerted upon it by the soil particle Thus, as evaporation proceeds, there is a redistribution of water in the soil in other words, there is a *capillary rise* The finer the system of capillary spaces, the more thoroughgoing is this upward movement of water from the surface of one particle to that of another We investigate the rate of capillary rise in various soils, *e g* sand, clay, and also chalk and humus thus —

130 Take a long piece of fairly wide glass tubing and cut it into lengths of about 1 or 2 feet each fill flower-pots, one with dry, sifted sand, others with clay and powdered chalk respectively (another may also be filled with finely divided peat) Push a tube into each flower-pot so that it is held firmly, pour finely-sifted, air-dry sand into the tube standing in the sandy soil, clay into the tube in the clay soil, etc , tapping gently the sides of the tubes to pack the materials Plunge the flower-pots in water to their rims and observe, by noting the change of colour of the soil, the rates of ascent of water in the tubes Contrast the capillary rise in the sand, clay, chalk, etc Draw or photograph the apparatus at the end of the experiment, and preserve the record in the museum

The picture of the structure of a soil which arises in the mind as the result of our experiments is that of innumerable particles separated from one another by spaces Around each particle is a film of water, and the remainder of each space is occupied by air As the root absorbs water, the films around the soil-particles in the neighbourhood of the root-hairs become thinner The surface-tension which the particles exert draws water from the films around the neighbouring soil-particles This in turn is absorbed by the roots, which thus obtain water from a large area of the soil In course of time, if no fresh supplies of water reach the soil, the osmotic pressure set up by the root-hairs is counterbalanced by the surface-tension exerted by the soil-particles, and the root ceases to absorb water

The soil, however, loses water not only to the plant, but also by percolation and by evaporation Hence the horti-

culturist, who cannot always supply water to the soil, has often to take steps to preserve the water in a drying soil.

This may be effected, for example, by spreading lightly over the surface of the soil a layer of fine particles, *e.g.* of finely-sifted, dry soil. By this means, the continuity of the network of capillary tube-like spaces, which extend from the depth of the soil to the surface, is interrupted at the surface, and, evaporation of water from the top layer being checked, the capillary rise of water from the deeper layer ceases. It is as though an infinite number of minute bungs were put in the necks of as many capillary bottles. On the other hand, if the fine surface-layer is pressed down firmly, for example, by rolling, and its particles thus brought into close contact with those of the layer beneath, capillary continuity is re-established, the particles of the top layer are able now by surface-tension to obtain fresh supplies of water from that surrounding the particles with which they are in contact, and hence, as the water of their films evaporates, there is established an upward movement of water from particle to particle. Again, if, instead of finely-divided soil, a loose layer or mulch of material, such as straw, or grass cuttings, or leaves, is placed on the surface, evaporation is checked. This layer, not in capillary continuity with the soil-particles, may itself become dry, but cannot withdraw the water from the soil below. Thus, the capillary rise being stopped, the water in the soil is conserved.

It is of interest to observe how agricultural and horticultural practice have for one of their main objects the control of the water of the soil. Nor, when we realise the water-requirements of plants, is it surprising that this should be the case.

The rainfall of this country, though spread over many days, is not great. In the neighbourhood of London, the annual rainfall is about 24 inches. Of the rain which falls on a field, some runs off the surface, much passes by percolation to the deeper layers of the soil and is carried away by drainage, much is lost by evaporation during those parts of the year when the fields are unoccupied by crops. Only that which remains is available for the plants

That there is apt to arise a shortage of water, and the crop is likely to suffer, is evident when we sider how considerable are the water-requirem various crops Thus, the amount of water taken the soil by a crop of wheat is equivalent to a rainfal the whole wheat-field of no less than six inches crops are yet more thirsty, mangolds, for instance, from the soil the equivalent of 10 6 inches, or some like half the total, average annual rainfall in so England

It is in consequence of the annual risk of water-l among crops that tillers of the land are at such pa interfere with nature in the interest of the crops cultivate Thus, autumn ploughing, by breaking t surface layers of the soil, increases its water-h capacity and, as the frosts of winter cause the cl crumble, the water is conserved by the interrupti capillary continuity

The practice of hoeing, resorted to by all good gard has a doubly beneficial effect In the first place, it down weeds, which compete with the cultivated plan the water or other materials in the soil, in the s place, by breaking the upper layer of earth, a lin is established and water is conserved in the soil

How important are the effects of hoeing may be j from the following figures, which give the loss of from hoed and unhoed areas of soil, deduced from an experiment :—

Daily loss of water from cultivated soil, 14 5 tons of water per
" " " uncultivated " 17 6 " "

In this experiment, soil cultivated to a depth of 3 was sampled at intervals to a depth of 6 feet C samples were taken simultaneously from adjoining with a firm surface

There was thus during the 30 days of the experi saving of water corresponding to 1 7 inches of rai

We must not bring these studies of the soil to without considering the soil, albeit in the briefest m from another aspect, namely, the biological

The soil is rich in many forms of life Beside the flow

plants, it bears ferns and toadstools Sometimes a green scum of minute algae may be seen on its surface, and by appropriate methods a rich flora of non-green organisms fungi, bacteria, and also a fauna of minute, unicellular animals may be discovered to have their homes in the upper layers of the earth

Though, however, the parts played by the soil-flora and fauna in determining fertility are of the greatest importance, we can consider them here in the light of but one example

131 Repeat Exp 106, but mix with the sterile sand in one of the pots about an ounce of ordinary garden soil Water this pot, and those containing sterile sand only with culture solution lacking nitrogen (Appendix A) Observe that the peas growing in sand to which the earth was added, though they may remain puny for a while subsequently grow as vigorously as those planted in garden soil Those in sterile sand remain small After some weeks, turn the plants out of their pots and observe that whereas those which have grown vigorously have curious nodules or swellings on their roots, those in the sterile sand have none Keep the specimens for the museum

132 Germinate seeds of gorse (Ulex europæus), some in sand sterilized by heating in a hot oven, and others in ordinary soil Observe the development of the seedling and the relation between their growth and the presence of nodules Dig up any leguminous plant from the field or garden (vetch, lucerne, lupine, etc), and observe its root nodules From laborious investigation of these root nodules, it has been proved that they are the result of an infection of the root by a definite micro-organism, Pseudomonas radicicola, and it has been demonstrated that this micro-organism, even when isolated in artificial cultures in the laboratory, has the power of obtaining its nitrogen from the free nitrogen of the air This it does also when it lives in partnership (symbiosis) with the roots of leguminous plants These plants, however, not only tolerate the micro-organism which multiplies in the cells of their roots, but eventually digest it, and so secure the nitrogen which the micro-organism has amassed We thus learn that micro-organisms exist in the soil which have the power to "fi

free nitrogen," that is to bring the nitrogen gas of atmosphere into such combinations as serve plants food-materials

We may understand how all-important this fact is w we remember that the amount of combined nitro (nitrates, etc.) in the soil at any given time is but small, t plants are constantly taking toll of it, that, in the decay plants and animals, the complex proteins are broken d by various micro-organisms, in ordered stages, to l ammonia and ultimately nitrogen. The nitrogen so for escapes into the air, as may also some of the ammo There is thus, as it were, a constant leakage of nitro from the living world. By the agency of the nitrog fixing bacteria, some species of which occur in the nodu of leguminous plants and other kinds of which live clusively in the soil, this escaped nitrogen is once m brought into combination and rendered available for nutrition of the higher plants.

It is more than probable that the general shortage nitrogen in earth and sea has led to other relations betw organisms as remarkable as that between legumin plants and Pseudomonas radicicola.

133 * Thus, when we examine with lens and microsc the young roots of forest trees, *e.g.* pine, oak, hornbe etc., and also those of heath plants, we discover th instead of root-hairs, the young roots are covered w mantles of fungous threads (mycorhiza).

It is not unlikely that, as a result of this symbio the flowering plants which take a part in it obt increased supplies of nitrogen. The lichens which gr on rocks and tree stems and other situations repres symbiotic partnerships between fungi and algae. No few animals, of which the green hydra is an exam are associated always with green algae. It is poss that all these strange symbiotic unions have for their si ficance the solving of the problem of obtaining adequ supplies of nitrogen.

CHAPTER IX

THE absorption and loss of water by the plant The water requirements of various types of plants —hygrophytes and xerophytes The process of the transpiration of water by the leaves the structure of the leaf in relation to this process the part played by stomata the opening and closing of stomata and the conditions under which these movements occur Apparatus for measuring rate of transpiration—(Potometer)

Now that we have completed our studies of the properties of the soil and the bearing of these properties on plant-life, we have to discover what becomes of the water and mineral substances which are taken up by the root-system

As a preliminary to this work we proceed to ascertain experimentally the amount of water absorbed by the roots of various plants The most accurate method is to measure absorption directly, a simpler way is that given in Exp 137

134 To employ the first method, germinate maize or other seeds used in water-cultures (Exp 109) so that the roots of the seedlings grow into a normal culture solution Prepare two tall glass vessels, each provided with a graduated side tube (Fig 23) Fill the vessels with normal culture solution to within an inch or so of the top, transfer a well-developed seedling to one of the vessels so that its roots are in the solution Fix its stem in a split cork which fits into the neck of the vessel By means of paraffin or wax, (Appendix A) make air-tight the junctions between cork and glass, and cork and seedling Plug the side tube with a wad of cotton wool to keep out dust Wrap black cloth round the vessel in order to exclude light from the roots and thus to prevent the growth of

green algae in the culture solution, but leave the side uncovered Fix a thermometer by rubber bands to side tube Proceed in a similar way with the other ve Label the vessels A and B, place them in a good light, continue, for as long a period as possible, to take records, by reading the level of the fluid in the side t

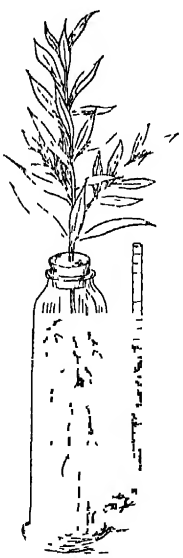

FIG 23 —APPARATUS FOR MEASURING ABSORPTION OF WATER BY PLANTS

of the amount of water absorbed by the plants Note day the temperature of the air and also the state o weather, fine and bright or wet and dull Add culture solution whenever necessary

Determine the total amount of water absorbed by A B, plot the daily amounts on squared paper, and "curves" of the amounts of absorption Observe relation which appears to exist between weather and an of absorption Since the volume of water absorbed b

plant during the course of the experiment is many times that of the plant itself, it follows that the water is either decomposed or else given off by the stem or leaves. The readiest method of demonstrating that water is given off from the plant consists in covering it with a bell-jar and observing that drops of water condense on the inner surface of the glass. Or we may use our plants A and B for the purpose thus —

135 Weigh the apparatus containing plant A. After two or more days weigh it again. Determine that the loss of weight of the apparatus corresponds approximately to the weight of water absorbed by the root during the period of the experiment.

Next demonstrate, in the following way, that the loss of weight recorded in the preceding experiment is due to loss of water by the plant.

136 After weighing apparatus B and recording the level of the liquid in the side tube, close its side tube with a cork and cover the plant in B with a large bell-jar, under which is placed a weighed vessel containing calcium chloride. The rim of the bell-jar must be sealed by wax to a flat block of wood or to the table, in order to prevent the calcium chloride, which is very hygroscopic, from absorbing water from air entering the bell-jar from outside. After 12-24 hours remove the bell-jar and also the cork from the side tube, weigh B and weigh the vessel containing the calcium chloride, by reading the level of the liquid in the side tube, determine the amount of water absorbed by the plant during the course of the experiment. Observe that the loss of weight of B is about equal to the gain in weight of the calcium chloride. Since the increase in weight of the latter is due to absorption of water, we infer that the loss of weight by the plant is due to loss of water. Hence it follows that the water absorbed by the root-system passes up the stem and is given off into the air in the form of water vapour, leaving behind in the tissues of the plant the mineral substances which it held in solution. Evidently therefore one important function of the water absorbed by the root is to act as a vehicle for the carriage of the mineral salts from the soil *via* the root to the shoot. The

fact that the loss in weight of plant B (Exp approximately equal to the weight of water abs the root during the same time does not mean other processes involving change of weight are in the plant, but that the amount of change i due to such processes is, during the short tim experiment, small in comparison with that due t water

The second and simpler method which we use to absorption is based on the fact, which we have jus strated, that the amount of water absorbed in a g by a herbaceous plant is about equal to the amo off as vapour It consists in putting pot-plants u conditions that evaporation from soil and pot is p and then weighing the plants at intervals Loss is due mainly to loss of water amount of loss of approximately equal to amount of absorption loss of weight gives a rough measure of amount o tion

137 The apparatus is made as follows —Ch leafy sunflower or dwarf bean plants grown in sn Procure marmalade or other jars, each large enoug one of the pots After watering the plants thoro the superfluous water drain away and stand the pieces of tile placed at the bottom of the jars a sheet of American cloth cut out two circul to serve as covers for the jars Make a cut in e extending from the circumference to the centre centre, cut out a small circular piece to allow of passing through Place each cover in position cut edges together by means of stitches, turn down over the rim of the jar and tie it firmly by several turns of stout thread Or the same end preventing evaporation from the soil, etc —may by getting a tinman to cut out for each jar t circular pieces of tin, each notched to enclose Two such tin plates, when fixed by wax to one an to the edge of the jar, make a good cover pots A and B It will be necessary from time t remove the covers and add measured quantities From the series of daily records of the loss of

the plants, calculate the total amount of water which they have given off during the time of the experiment (cf Exp 136)

We determine next that the water given off escapes mainly from the leaves

138 After weighing the two vessels with their plants (using the apparatus either of Exp 134 or that of Exp 137), remove about half of the leaves from plant B Weigh the apparatus again, replace it and take a daily or 48-hourly record of its loss in weight Whilst the cut-off leaves are fresh, determine their area (Appendix B) Note that the rate of loss of water by the plant from which leaves have been removed is considerably less than it was before Remove the remaining leaves and estimate their area From the records obtained, calculate the rate of loss of water *per unit of area*, say per 10 sq cm of leaf surface We thus demonstrate that the amount of loss of water, or, as we say, the amount of water transpired, is roughly proportional to extent of leaf surface, and infer therefore that the water escapes mainly from the leaves Since a small quantity of water is also given off from the stem, even after the precaution of covering, *e g* with collodion, all the wounds formed by removal of the leaves, it may be necessary, in making this calculation, to deduct the amount of water given off by the leafless plant from the amount given off by the plant with half its leaves, and from that with all its leaves intact In the foregoing experiment, plant A—with its leaves intact—serves as a control We know the relative rates of transpiration of A and B over a period of many days We know the rate of transpiration of A during the period of the experiment Hence we can calculate approximately the amount of water which B would have lost if its leaves had not been removed, and we are able to compare the rate of loss of B with all its leaves with that of B with half, and with none of its leaves By continuing to record the transpiration of plant B for some days, we may observe that though it is very much reduced, some loss of water occurs after all the leaves have been removed, and conclude that, though the leaves are special organs for allowing of the escape of water vapour, other parts, par-

ticularly the delicate green parts of the stems, may a
give off water vapour

Plant B is now useless for further experiment, but pl
A should be grown for as long a period as possible, a
regular records of the rate of transpiration made, tabulat
and the record-chart kept in the museum

Having gained precise information with respect to
large amount of water taken up and given off by plants w
thin delicate leaves like maize, sunflower or bean, we p
ceed to find out whether plants with other types of lea
are equally spendthrift of water For this purpose,
any pot-plants the leaves (or stems) of which are thick
fleshy, *e g* Agave, india-rubber plant (Ficus elastica),
cactus with fleshy stems, a Mesembryanthemum, or, fail
any of these, gorse (Ulex europæus) grown in pots.

139 Having fitted up a broad, thin-leaved plant (
e g sunflower, in a marmalade pot A (Exp 137),
in apparatus B one of the just-mentioned plants Det
mine, by weighing daily, the rates at which A and B l
water After some days, determine the areas of the lea
and stems of the two plants and calculate their rates
transpiration per unit of area

The following is a record of the rate of transpi
tion of two plants placed under similar conditions
twenty-four hours It shows that the rate of transpirat
per 100 sq cm of surface was 32 7 times as great
the case of Hydrangea hortensis, a plant with relativ
large and thin leaves, as it was in that of Opuntia cylindri
a cactus with a fleshy green stem and no leaves

	Transpiration per 100 sq cm of surface
Hydrangea hortensis -	6 54 gm
Opuntia cylindrica - -	0 20 ,,

We learn from these experiments that different kinds
plants have very different water requirements Some l
water and hence if they are not to wither, also take
water, much faster than others Not only is the loss
water per unit of surface much less in succulent
leathery-leaved plants than in plants with delicate leav
but also the total leaf-(or green stem-) surface of the for
is much less than that of the latter Since such succul

nts live generally in dry situations, we may infer that reduction of surface, the succulence of the leaf or stem, thick cuticular covering of leathery leaves, the matted is common on such Alpine plants as the Edelweiss ontopodium alpinum) are so many adaptations making water economy Such plants find water either hard to (desert-plants, alpines) or hard to keep (plants of hot ntries, agaves, cactuses, etc) or both Plants which nage to live in such situations do so by definite adapta- of their root-systems and shoot-systems the root- tem of desert-plants is often of extraordinary length— roots, as it were, going in search of water the shoot- tems display the most diverse adaptations serving to uce the amount of water given off from their surfaces se water-economising plants are known as *xerophytes* contradistinction to *hygrophytes* The latter are as ravagant in the amount of water which they absorb and e off as the former are niggardly

among British plants, note that those of sandy soils and er dry situations are xerophytes, *e g* the Scotch fir ius sylvestris), gorse (Ulex europæus), broom (Cytisus pariius), heaths and various grasses which grow in ir company

40. Specimens of these xerophytes and also of the mmoner hygrophytes—broad-leaved trees, etc —should collected, compared, and kept in the museum

Having learned something of the water requirements of ious kinds of plants, we next enquire how the water and s absorbed by the roots pass to the leaves, and how the es get rid of the large quantities of water which reach m We will first consider the latter question

Clothes hung upon a clothes line in the open air dry soon he weather is bright and warm Since, in the course of os 134 and 137, it has surely been noted that plants lose er more quickly on a bright or warm day than on a dull old day, it might be supposed that the loss of water by leaf is, like that of clothes hung out to dry, due solely to poration But, if this were the case, the plant would be gether at the mercy of its surroundings In hot, dry ther, when evaporation is high and absorption, owing to ness of soil, is low, the plant would wither, wilt and die

So it may, if the drought is prolonged, but not with inevitableness of the drying of clothes in bright wea from their behaviour in spells of dry weather, it look though plants did not give way to drought witho struggle, and that, though dry air causes evaporation clothes and plants alike, the latter, unlike the former, h to some extent at all events, means of preventing exc losses of water from their tissues We can imitate resistance of the plant to the last stages of desiccatio the following experiment —

141 Weigh two large saucers or basins, fill one wi known volume of water, the other with an equal volun fairly strong solution of sugar Weigh the vessels con ing the water and the sugar-solution Expose them warm place, and determine, by weighing, the rates of due to evaporation Note that, as the sugar-solution con trates, its rate of loss of weight falls off very consider Consider now a vegetable cell within its protopla (plasmatic) membrane is a vacuole r, s ete , in solution Enclosing it is a cell-wall substance and protoplasm contain imbibed wa Imagine a tissue made up of a number of such cells exp to a dry atmosphere the cell-wall loses water by evap tion and withdraws water from the protoplasm, whic turn withdraws water from the cell-sap The cell becomes more concentrated, and hence its osmotic press its attraction for water, is increased As evapora proceeds, not only is the imbibed water remaining in wall and protoplasm held more strongly, but also concentrated cell-sap, unless it is able to withdraw w from neighbouring cells and to become dilute again, oft like the sugar-solution of our experiment, more and n opposition to evaporation Thus we understand one in which the plant may resist extreme desiccation Be deciding, however, that this is the only method, we look at the leaf itself, for its structure may throw fu light on the subject

On inspecting various leaves, we observe that in n of them there are marked differences between their surfaces

142. Compare, for example, from this point of v

the following —beech, elm, holly, tulip, hyacinth, laurel, etc Note that in leaves which, in their natural position, lie more or less horizontally, the under side is paler than the upper side The surface exposed to the direct rays of the sun appears to be less delicate than the other, and looks as though it would allow water to evaporate from it less rapidly We prove that this is the case thus —

143 Take two similar leaves of the india-rubber plant (Ficus elastica) or the laurel (Prunus Laurocerasus) Slip a piece of thin rubber tubing over the stalk of each leaf Turn back the tubing, and, by means of wire, bind the loop thus made so as to block the hole in the tube and to make a convenient hook Smear with vaseline the lower side of one leaf and the upper side of the other Weigh each leaf Hang up the leaves in a room, and determine, by weighing at daily intervals, the rates at which the leaves are losing water.

144 Not all leaves, however, show this marked difference between under and upper side, and if the above experiment is repeated on the leaves of beech or broad bean, using in these cases *similar branches* with equal numbers of leaves, no marked difference between under and upper sides with respect to resistance to evaporation will be found This, however, does not affect the fact shown by Exp 143, that plants which require to reduce evaporation, and yet, at the same time, are obliged, for other purposes, to expose a considerable leaf-surface to the light, produce leaves the upper surfaces of which hinder evaporation more than the lower Microscopic examination will help us to learn more as to the nature of the differences between the upper and lower surfaces of leaves

145 * Mount a small piece of a leaf of the frogbit (Hydrocharis Morsus-ranae) or water starwort (Callitriche verna) in a drop of water, and examine it with low and high powers of the microscope Observe that, in one or other or both surfaces, there are large numbers of extremely minute holes These holes or *stomata* cannot be seen in thicker leaves when whole pieces are mounted Therefore, in order to examine ordinary, thick leaves for stomata, strip off, by means of fine forceps, or cut with a razor, pieces from the upper and lower surfaces of the leaves of the

plants mentioned below, mount each piece in water on slide, and determine that, in the india-rubber plant an laurel, stomata occur only on the under side of the lea whereas in the bean, beech and tulip they occur on bo sides The fact that the surfaces of leaves are not co tinuous but are interrupted by innumerable openings throw a new light on the results of Exps 143 and 144, and at one suggests the idea that water-vapour may escape not on from the general surface, but also through the stomat This becomes the more likely when we discover, by th following experiment, that the stomata are in communic tion with spaces running between the groups of cells c which the soft tissues of the leaf are composed

146. Attach firmly by wire a small piece of rubbe tubing to the stalk of a delicate leaf, *e g* marsh marigol (Caltha palustris) or wild arum (Arum maculatum) Im merse the blade in water and suck at the open end of th tube Note that the leaf becomes darker green owing t the entrance of water through the stomata If the surfac of the leaf is first smeared with vaseline, the stomata ar blocked and no water enters Or, if an air pump i available, connect it with the side tube of an Erlenmeye flask (Appendix B) containing water. Place a delicat leaf beneath the surface of the water Having close the opening of the flask with a rubber cork, exhaust th air by means of the pump Note that, as the pressur in the flask is reduced, bubbles of air escape from th cut end of the petiole and water enters through the blade Hence the stomata communicate with spaces—inter cellular spaces—which run between the cells of the leaf Hence also evaporation is possible not only from the sur face tissues of the leaf, but also from the cells of deepe tissues abutting on the air spaces For, if the air at th surface of the leaf is dry, water-vapour passes by diffusion from the air spaces through the stomata Thus the air o the spaces becomes drier, and, in consequence, wate evaporates from the cell-walls, in short, the internal cell neighbouring on the air-spaces lose water by the same process as that described for the cells on the surface of the leaf (p 150) We are not, however, to suppose that the purpose of this system of spaces and of stomata is neces

sarily to facilitate transpiration Their main function, for aught we know at present, may be of quite another kind, *e g* for allowing air to circulate freely in the leaf But whatever their main function may be (see p 161), the facts remain, that they are there, and that, therefore, they cannot but serve as channels through which water-vapour, given off by the cells abutting on them, escapes into the air That water-vapour does escape from the stomata we demonstrate thus —

147 Soak strips of filter- or blotting-paper in a 10% solution of cobalt chloride Dry them in a desiccator, and when not in use, keep them there or in a closely stoppered bottle Expose a strip to moist air, *e g* breathe on it, and note that it changes colour Cut off a leaf, place on either side of it a strip of cobalt chloride paper covered by a sheet of thin glass or mica, bind the glass close to the leaf by means of rubber-rings, lay the leaf on a clean table and cover it with a bell-jar or glass dish Observe the change of colour on one or both sides of the leaf and determine that stomata occur, in the one case, on one side, and, in the other, on both sides Instead of being cut off, the leaf may be left attached to the plant during the course of the experiment

148 * If a micrometer is available, determine (1) the number, (2) the size of the stomata either on strips from the surfaces of the leaves or on the whole leaves of Exp 145 It may thus be shown that the number of stomata in a leaf is almost incredibly large, ranging generally from 100 to 700 per sq mm of leaf surface *i e* from 50,000 to over 350,000 per square inch The size of each stoma is as small as the number of stomata is large on the average a stoma is about 0006 mm in diameter, *i e.* 000024 inch

Our discovery that the surface of a leaf is riddled with holes of microscopic size is a fact which has evidently to be taken into consideration in studying the mode by which water is given off by green plants As we have proved, the water lost by the leaf escapes in large measure not from the general surface but through the stomata Now, when we were examining these pores (Exp 145), we could scarcely fail to notice that each of them is bounded on

either side by a cell, the shape of which is diffe
that of the other cells of the surface layer (epider
leaf The cells which encompass the stomatal
called guard-cells In surface view, each guar
pears more or less sausage-shaped The guard
the further peculiarity that, whilst they are conn
one another at their ends, they are separated
middle line, the cleft between them constituting t

Having obtained an idea of the nature of ste
their guard-cells, we return to our problem
water by the leaf merely a matter of evaporation,
plant—as we suspect some power of regulatin
The only parts of the apparatus concerned in the
of water likely to be under the control of the pla
stomata Now, stomata are holes slits between
the plant could control the size of the stomata
amount of water-vapour escaping through them
haps be reduced in amount But if the stom
change in size, they can do so only by change in
or size of the guard-cells Therefore, we have t
the guard-cells fixed in position or are they mov

We know already that a cell, when it becom
increases in size, and that, when it is plasm
shrinks We proceed to ascertain whether ar
involving change in the stomata, occurs when
are rendered turgid or when they are plasmolyse

149 " Repeat Exp 145 on surface-sections o
Tradescantia or other convenient plants

The leaves of the following plants serve well fo
tions on stomata, as the epidermis may be remo
by the aid of forceps Primula sinensis, Pi
conica, Tropaeolum majus, Pelargonium zonale,
annuus, Tulipa, Vicia Faba

Note that whereas, when they are in water, th
are large or, as we may say, open, when a 10% so
is run in they become small, that is, they close n
that this change is effected by a change in shap
of the guard-cells A complete understandi
mechanics of this remarkable movement of
involves a detailed study of their structure, a
which we cannot now embark (Bibliography, 5,

Knowing that stomata are capable of being increased or decreased in size, we next enquire whether they actually change in size during the life of the plant, and if so, what are the conditions which determine the movements of the guard-cells by which the opening and shutting are effected? We therefore investigate the state of the stomata in plants which have been subjected to diverse conditions, *e g* bright light, darkness, dry air, moist air, lack of water at the root, etc

To make the observations, we require a better method than that employed in Exp 145, though the plants used in that experiment will serve admirably The method we use is as follows —

150 * Expose growing pot-plants for an hour or so (1) to bright light, (2) to darkness, (3) to dry air (see Exp 136), and also cut off leaves and allow them to wither Throw the leaves treated in these ways into bottles containing absolute alcohol, stopper and label each bottle, expose the bottles to sunlight till the leaves are colourless Transfer the leaves to another bottle of absolute alcohol After an hour, take them out and plunge them into a bottle containing xylol When the leaves are transparent, mount small pieces in cedar wood oil and examine under low and high powers of the microscope Conclude from the experiment that the stomata of the leaves of many plants close in darkness, in dry air, when the soil is dry, and when the leaves wither, and that, on the contrary, they open in bright light and in moist air

It is evident that certain of the conditions which make for the closing of stomata are conditions under which loss of water by evaporation tends to become excessive, *e g* in dry air On the other hand, it is *not* evident that change from light to darkness—apart from attendant temperature change—results in a reduction of the rate of evaporation Let us ascertain, therefore, whether change from light to darkness produces any change in rate of loss of water by the plant If it does, we shall be justified in concluding that the opening and closing of stomata serve, to some measure, to regulate transpiration We shall not, however, be justified in concluding that this is the primary significance of these movements For, as we have suggested already, the stomata are not merely concerned with

transpiration, but also with exchange of gases l plant and air, and it may well be that the opening stomata in the light and their closing in the d. concerned primarily with the regulation of gase change, and only indirectly with transpiration

In order to investigate the effect of external con light, darkness, etc., on the rate of transpirati require a more delicate apparatus than that used i 134 or Exp. 137, though for certain experiment 153 and 154) either of those may be employe principle on which our more delicate method is b as follows —

151. The rate of transpiration by an herbaceous about equal to the rate of absorption (p. 145). Si water absorbed passes from the root to the leaves, pass through the stem. Therefore, if we connect th of a living plant with a narrow tube, we may be able the water passing up the tube and to measure the which it passes. Such an apparatus, called a pote may be of one of several forms. That shown in F and designed by Professor Farmer, consists of the ing parts —A wide-mouthed bottle which is fitted rubber cork pierced with three holes, the middle hol just large enough to admit of the passage of the s a fair-sized leafy branch. A thistle funnel provide a stop-cock is fitted into one of the other holes, a the third, a bent tube of narrow bore is passed, so th end is flush with the inner surface of the cork.

Another type (Fig. 25)—the original form devi Francis Darwin—consists of a glass tube with limb, to the free end of which a short piece of rubber tubing is attached securely by wire. branch of the plant to be used in the experim passed through the rubber tube into the limb of the vessel and fixed firmly by wire wound round the tubing. When in use, the upper end of the straigh is closed by a well-fitting cork, and the lower end i with a rubber cork with one hole, through which a glass capillary tube of about five or six inches in l In setting up either apparatus, the following piece are to be observed:—

(1) Cut off the branch under water, *e g* by bending it down beneath the water contained in a basin or pail

(2) Keep it for some hours with its cut end under water, *e g* if a laurel branch is used, cut it off in the evening and use it the following morning

(3) Before it is put into the potometer, remove a short length ($\frac{1}{4}$ inch) of the cut end by means of a sharp razor (making the cut under water)

(4) When inserting the branch, fill the potometer with water and submerge it in a sink or pail filled with water

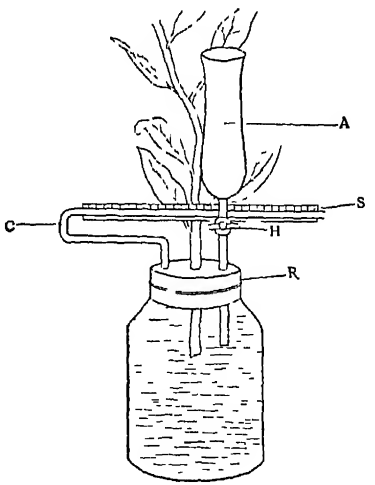

FIG 21.—POTOMETER (AFTER FARMER)

A, funnel with stop cock (H), C, glass tube of narrow bore, S, scale, R, rubber cork

(5) Fill a tumbler with water, insert the cut end of the branch in the tumbler, carry it to the sink, submerge the tumbler and transfer the branch to the potometer If the bottle-potometer is used, submerge the rubber cork and pass the cut end of the branch through the middle hole so that, when the cork is inserted in the neck, the branch projects into the bottle Press the cork into the bottle, close the stop-cock, pour water into the thistle funnel, and

lift the apparatus out of the water See that th
between cork and branch is good if not, dry t
and make the joints air-tight with wax (App
Place the apparatus in a good light and fix a sc
the narrow tube, or make on it india-ink m
distance of three or more inches from one anot

If the tube-potometer is used, submerge it, an
the cut end of the branch from contact with ai
branch through the rubber tubing, wire it by t
turns of thin wire passed round the rubber tubin
the joint has been made good, push in the co
the capillary tube, cork the upper end of th
limb, lift the apparatus out of the water
it in the clamp of a retort stand Adjust the ap
that the free end of the capillary tube just dips u
glass vessel containing water and standing o
block of wood Make two india-ink marks a
inches apart on the capillary tube

One advantage of the bottle apparatus is th
use, air may be prevented from accumulating in
for when air has passed some distance
narrow tube it may be driven back by turning the
and allowing water to enter the vessel from
funnel When not in use, attach by means of
rubber tubing, a bent glass tube to the free e
narrow tube, and allow its end to dip in wate
to prevent the entrance of air

To use the tube apparatus, slip away the w
remove, by means of blotting-paper, a drop of w
the free end of the capillary tube so as to adm
bubble of air, replace the vessel and block so
again enters Time, by means of a stop-watch, th
of the air bubble from the lower to the upper ma
the time Admit another air bubble, repeat th
and so on If the branch is losing water rapidl
of passage of the bubbles is very fast, and a fe
suffice to give 10 or 12 readings

When the bottle-potometer is used, the end of
column in the narrow tube is followed and t
takes to pass from mark to mark recorded It
back by opening the stop-cock and admitting

ittle Thus a series of readings may be obtained An ge of the series gives the rate at which water is passing

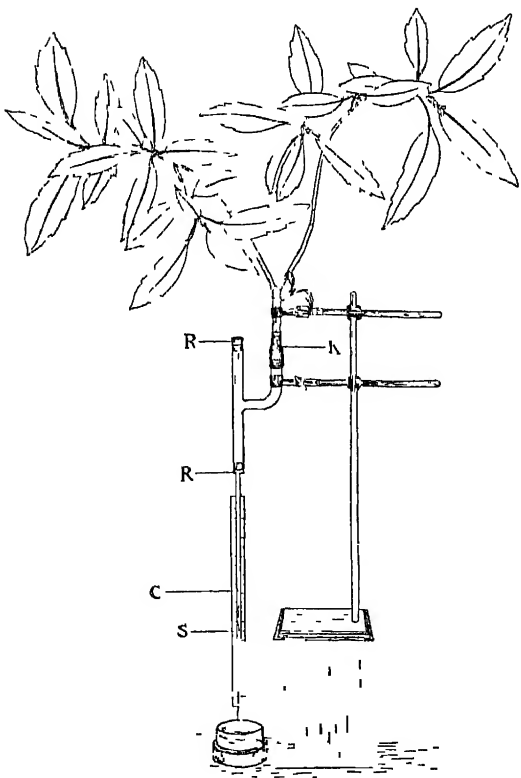

FIG 25 —POTOMETER (See p 156)
C, capillary tube, S, scale, R R, rubber corks, K, rubber tubing

he cut end of the stem, and since, as we have shown, ate is, generally, proportional to the rate of transpira- our potometer gives us a measure—albeit an indirect -of the rate of loss of water by the leaves The chief

value of the apparatus, however, lies in its quick comparative records in such comparis assume that, if under one set of circumstances, pass, on the average, twice as quickly as under the rate of transpiration is twice as great in th in the latter circumstances The records transpiration now to be taken should be acco temperature-records

152 Expose the apparatus in the window record the air temperature, take a series of re determine the average rate at which water is pa the graduated tube Transfer the apparatus t and set it in a breezy, shady place, after a take a series of readings Expose it in the ope sunlight, and, after an interval, make anothe readings Replace it in its original position, a quarter of an hour, take readings Put it in a leave it for about half an hour, and make a series The plant may be screened from the light (e g used in reading the rate of passage of the bubbl

153 Put a small leafy branch in the tube having taken a series of readings in ordinary ai branch with a bell-jar, provided, if not oth enough, with a "flounce" of glazed calico M thoroughly moist, e g by syringing water und jar (avoiding wetting the leaves) Record bell-jar, and after an interval take a series of ordinary air

154 Having dried the bell-jar, replace it ove and put under the jar a large dish contain chloride Take readings, one series at once, a about half an hour

The conclusions which we draw from the re foregoing experiments are as follows In the conditions which favour evaporation favour tr (Exps 152 and 154) In the second place, tr decreases in darkness and increases in light, fact that the temperature may be considerab the dark room than in the open air is in part for the lower rate of transpiration in the forme

Bearing in mind that the stomata of many p

in darkness and open in light, that they may close in dry air or when the plant is dry at the root, and that they open under circumstances in which evaporation is reduced, we may conclude that, though transpiration is set up as the result of evaporation of water-vapour from the air-spaces surrounding the cells of the leaf, though it is hastened by conditions which favour evaporation, and checked by conditions which hinder evaporation, the process of transpiration is not a mere evaporation For, on the one hand, the living cells resist desiccation automatically, as they become drier, so the contents of their sap concentrate, the osmotic pressure increases, and water is held more strongly On the other hand, by the opening and closing of its stomata, the plant regulates to some extent the rate of loss of water As the guard-cells lose water, they decrease in size, change in shape, and come closer together, so that the stoma between them is made smaller If water is supplied plentifully, *e g* by wetting a leaf, the guard-cells become turgid, the stomata open, and the rate of transpiration tends to increase Whether the prime purpose of the movement of stomata is to secure this end, or whether this is a secondary matter, we cannot decide It may be that, as the plant loses water, it becomes important for it to shut down *all* its activities, and that the closure of the stomata serves to secure this end by reducing the rate of gaseous exchange between the plant and the air

CHAPTER X

THE passage of water from root to leaves the channels followe
the transpiration current water conducting wood and skeletal w
The causes of the ascent of water Phenomena connected with
absorption of water root pressure bleeding excretion of w
water-pores (hydathodes)

OUR previous studies have taught us that of the w
absorbed by the root hair-cells, some passes to neighbo
ing living cells and, absorbed osmotically by them, c
tributes materially to the increase of weight manifested
the growing plant The water used in this way is, h
ever, but a small part of that taken up by the root
far the larger part of the water absorbed travels,
we know, from the root to the leaves, whence it pas
into the air in the form of water-vapour The stream
water which passes through the plant we may call
transpiration current, and we require to learn what are
channels along which this current travels in its pass
from the root to the leaves That the transpirat
current passes along definite channels we demonstrate
the following way —

155 Dig up one or two well-grown seedling bean
pea plants, wash their root-systems free from earth,
across the main roots, place the plants with their roots
water in which is dissolved some dye, *e g* eosin or
ink, and leave them exposed to the light till the col
of the dye is visible in the "veins" of the leaves a
also, if the plants are in bloom, in those of the flowe
Cut the root and shoot of one specimen transversely i
a series of pieces, examine the cut surfaces by mea
of a lens, and determine that the dye has travelled

the stem along definite tracts Note that the position of the stained areas is not the same in the root as in the shoot

156 * Mount transverse sections of the stem in water or dilute glycerine, and examine them microscopically Note that the tracts along which the dye has passed contain what appear to be largish spaces, each surrounded by a fairly thick and stained wall Observe that the dye which stains the walls of the relatively wide water-channels is absent from the cellular tissues of the stem By means of similar cross-sections, follow the course of the dye from the shoot, through the leaf-stalks to the "veins" of the leaf

157 Cut the root and shoot of the second plant lengthwise, proceeding cautiously from below upward, and trace the longitudinal course of the dye By the aid of the microscope, observe, in thin longitudinal sections, that, whereas the tissues of the part outside the stained areas are made up of minute cells, those in the stained areas contain long and wide tubes, the walls of which are curiously thickened in an annular, spiral or other regular manner These dead elements are, as the dye indicates, the channels (vessels) along which the water passes to the leaves On tracing them towards the leaves, the vessels are found to connect with similar, smaller groups which run in definite courses through the leaf-stalks, and are distributed in the 'veins" throughout the leaf Some idea of the length of individual vessels may be obtained in the following way —

158 To ordinary leaf-gelatine add so much water that it remains liquid at about 35° C , but sets to a solid mass at room temperature Colour the fluid gelatine with eosin, and pour it into a tall jar, *e g* a measuring vessel, stand the latter in a large beaker or saucepan containing water which is kept at a temperature of about 40° C by means of a bunsen flame Plunge the cut end of a leafy branch below the surface of the gelatine, and leave it for an hour Remove the vessel containing the branch from the beaker of hot water, plunge it under a tap, and allow a stream of cold water to fall on it so as to cause the gelatine to set When the branch is cooled, take it out of the gela-

time, cut it longitudinally, and determine the length the stem along which the gelatine may be traced In much as the gelatine is free to pass into the open ends the vessels exposed on the cut surface, but cannot p across the end walls of the vessels, we obtain a rou measure of the length of the vessels in the plant on wh the experiment was made

By more accurate methods it has been demonstrated tl the length of vessels varies very considerably in differ plants Thus, in the oak, they have been estimated to 2 metres or more long, in species of fig (Ficus) they ran from 10 to 66 centimetres, whereas the much shorter co ducting elements (tracheids) of the Scotch Fir (Pi sylvestris) are only about 4 mm in length

159. Whilst the previous experiment is going on, c off two similar branches, *e g* of laurel, stand one w its cut end in water, and plunge the cut end of the oth beneath the surface of melted coco-butter After abo quarter of an hour, remove the branch, cool its cut en make a fresh cut about a quarter of an inch from t exposed surface, stand the branch with its cut end in wat in bright light, and observe that, owing to the vessels havi been blocked by the coco-butter, the leaves wither far soon than those of the branch which was placed at once in wate

The conclusion that water passes through the *cavitie* of the vessels may be verified thus —

160 Set up a well-grown branch of sunflower (He anthus annuus) or Jerusalem artichoke (H tuberosus) a potometer (Exp 151), and determine its rate of tran piration Fix the middle of the branch in a vice and scre the latter so tightly as to compress the stem and hen its vessels Observe that the rate of transpiration fa off very markedly Release the stem from the vice an ascertain that the rate of transpiration increases

The microscopic examination of the cross-section of th bean stem of Exp 155 showed us that the vessels a distributed in isolated groups

161 That this is not their distribution in older sten we recognise by observing with the aid of a lens the cr ends of two-, three- and more year-old branches of wood plants, *e g* trees such as lime, lilac, etc In these plant

the wood forms the greater part of the stem, and the vessels, which make up the larger part of the wood, are seen to be distributed uniformly throughout the woody tissues

The process by which the wood is increased from isolated strands to a solid cylinder may be studied in text-books of plant-anatomy (Bibliography, 5, 6), but, by comparing the cut surfaces of one-, two-, and three-year-old branches with one another, we observe that each year a new ring of wood is formed on the outer side of the old ring We note further, that there are fairly sharp lines of demarcation —the annual rings—between each year's wood and that of preceding and successive years With a good lens, or by microscopic examination of sections, observe that the appearance of these concentric annual rings is due to the fact that the vessels which are the last to be formed in late summer of one year are thicker-walled and have smaller cavities than those which are the first to be formed in the spring of the ensuing year We conclude that in our native perennial plants, which possess well-marked annual rings, it is possible to determine the age of the tree by inspection of the surface exposed by a cross cut Though we cannot now study the question as to the cause of these marked differences between the wood formed in spring and that formed in late summer, we may remark that it is only in regions like our own, in which vegetation is subject to a distinct seasonal check, that the wood shows well-marked annual rings

Our main object in referring to this matter is to ask ourselves the question, whether all the vessels of the wood are capable of conducting water, or whether this task is discharged by certain vessels only? The fact that there are to be seen hollow trees, such as willows, which have lost much of their older wood—that nearer the centre of the trunk—seems to indicate, that at all events in such plants, the young wood suffices for water-conduction The first step towards an answer to this question we make as follows —

162 Obtain four, similar, leafy branches of some tree, *e g* oak, elm, etc , and stand them with their cut ends in water coloured with eosin or red ink Having formed a clear idea of the extent of the wood by inspection of the cut

surfaces, remove a ring of bark from the stem of o specimen (No. 1), avoiding cutting into the young woo Slip a rubber band around the stem of No 2, and, usi the edge of the rubber band as a guide, make a circu cut with a sharp knife into the bark and young woo In No 3 make a similar circular cut, but so deep t only the oldest, central heart-wood remains intact Ma no incision into No 4 Ascertain, by the potometer meth (Exp 151) or by observing the rates of withering of t leaves, what parts of the wood are concerned specially wi water-conduction

By means of such experiments on different plants demonstrate (1) that the parts of the stem external to t wood are not concerned with the transmission of the wate current along the stem, (2) that the young wood is specia concerned with water-conduction, (3) that the older wood such trees as oak is incapable of conducting water, thou in others, *e g* lime, it aids the young wood in this wor In those trees, the old wood of which has ceased to ser the purpose of water-conduction, it may be noted th marked differences of colour, etc, exist between old a young wood, in these cases, the difference between young splint wood (albumum) and older heart-wood (duramen) made visible It will be evident that though the heart-woo of a given tree has ceased to conduct water, it nevertheles may play an important part in acting as an intern skeleton to the trunk, and thus giving it the power resisting the shearing action of wind and providing support for the ever-increasing crown of branches whi the tree puts forth Though we are not now making thorough study of the structure of wood, we must satis ourselves that the woody tissue does not consist e clusively of vessels, but contains other elements, some which may be shown by appropriate tests (Bibliography, to be unlike the wood, not only in size, but also in t fact that they contain living protoplasm and also reserv substances, such as starch

We are now able to picture to ourselves the wate conducting system of the plant Below, in the soil, a the root-hairs, the organs for the absorption of wate The inner walls of the root-hair cells adjoin those of t

cortical cells which absorb, according to their osmotic capacity, water from the root-hair cells and become turgid The innermost cortical cells are in contact with others of the deeper-lying tissues, and these, in turn, abut on the vessels In its young stage, a vessel, which is formed from a longitudinal row of cells, is a living element, and, like all living cells, contains osmotic substances Hence water passes by osmosis into the developing vessel The constituent cells which are forming the vessel increase in length, their cross walls disappear, their longitudinal walls thicken, become lignified (woody), and are rendered rigid by the bars or rings or spiral bands of woody substance formed, as the last act of the protoplasm, on their inner surfaces Thus, the completely developed vessel is full of water Each such vessel of the root connects above with a similar older vessel, the cavities of the two vessels being separated only by a thin membrane which constitutes the end walls of the two vessels Across this membrane, water and dissolved substances pass readily If we think of the plant as it grows from the seedling stage, we can picture new vessels filled with water being added in root and stem by the development of rows of cells some distance behind the growing points, and hence we can imagine continuous columns of water in each of the longitudinal series of vessels which extend from the veins of the leaf, through the stem, to the root Now, it has been shown that a continuous column of water, such as we have imagined to exist in the longitudinal series of vessels in the plant, has very remarkable properties Even though it is subjected to a considerable pull, the column does not break We know that, in the plant, water is evaporating from the inter-cellular spaces of the leaves into the air, and that this process sets up a chain of events, resulting in the withdrawal of water from the vacuoles of the green cells Hence the osmotic pressure of these cells is increased, and they withdraw water from the colourless cells with which they are in contact The colourless cells, abutting on the vascular elements in the veins of the leaf, absorb water from these elements But as we have pictured the conditions, these vascular elements contain the tops of continuous water-columns, which extend through the stem to the

root As water is lost above, one of two things must happen, either the water-column must break, or the column as a whole must be hauled up It can be shown experimentally that such a column does not break, even when subjected to a very considerable pull Hence we may infer that it is hauled up bodily Thus it may be in this manner that the ascent of water is effected even in great trees, such as the Eucalyptus of Australia, or the Sequoia of Western America, which reach a height of about 300 feet

It should be noted that we do not offer proof that this is actually the mode by which the ascent of water is effected, we may, however, adopt it as an hypothesis to account for the fact—which is one of the most remarkable in the whole range of plant-physiology—that a tree is able to haul up large quantities of water to a very great height Although it must not be regarded as a model illustrating the mechanism of the lift of water which takes place in transpiration, it is none the less instructive to make an apparatus which shows that, when water is evaporating from a surface connected with a water-column, a considerable "pull" is exerted For this purpose we proceed as follows —

163 Soak a piece of parchment membrane in water and tie it tightly over the wide end of a thistle funnel Fill the funnel *completely* with boiled water, and, closing the narrow end with the finger, stand it with the wide end uppermost in a dish containing mercury Place a scale behind the apparatus and record from day to day the height to which the mercury is lifted in the tube as a result of evaporation of water from the surface of the parchment

164 A better apparatus, but one that requires a little skill to construct, is made by causing plaster of Paris to set so as to form a layer closing the mouth of the funnel The apparatus is filled with water, and in this, as in the previous experiment, it is important that the water used should be rendered by boiling as free from air as possible, since the air contained in unboiled water, being liberated as evaporation proceeds, accumulates beneath the surface of the plaster and tends to break the continuity between

the water in the plaster and that in the tube That the transpiring plant exerts a similar pull may be demonstrated in a similar way as follows —

165 Cut a branch from an actively-transpiring plant and stand it for some hours in water Fit it, by means of a split cork, into a vertical tube filled with water This may be done by plunging the tube and the cut end of the branch in a pail of water and placing the cork in position Raise the tube, fix it in the clamp of a retort-stand, wipe the cork dry, and make the joints air-tight by means of a layer of wax Whilst the lower end of the tube is closed with the finger place the apparatus so that it just dips into a dish containing mercury The rise of mercury in the tube is then recorded as in the previous experiment

Another experiment may now be performed to demonstrate the fact that the activity of the roots in absorbing water may, especially at certain seasons of the year, set up a considerable pressure in the plant, which is described as *root-pressure* Not all plants exhibit this phenomenon, and hence root-pressure is not to be regarded as an agent effecting the ascent of water The experiment may be tried on any convenient vigorous plant Sparmannia africana, or species of Phaseolus or Fuchsia are suitable for the purpose

166 Give the pot-plant selected for the experiment a thorough watering Cut back the stem to within a few inches of the soil Slip a piece of rubber tubing over the cut end and wire it securely, pour in a little water and fix, by means of wire, a long glass tube of fairly narrow bore in the other end of the rubber tubing Place a scale behind the tube and record at intervals the height of the water in the tube In the case of trees and shrubs in the open, experiments to demonstrate root-pressure succeed best in spring before the leaves are fully expanded The phenomenon of root-pressure may be connected with others occurring in nature For instance, under certain circumstances, vines, especially when pruned late and with the wounds imperfectly healed, exhibit a "bleeding" process In the spring, sap containing various substances in solution exudes from the cut ends of the shoots

The quantity of fluid which may escape b
is often considerable, *e g* from birch, sug
palms, etc. The liquid which escapes from t
flower-stalks of certain palms is so rich in suga
used in Ceylon and Java for the manufacture o
liquors In some cases, this exudation or ' blee
be due to root-pressure, but, in others, it is th
pressure set up locally, often as the result of a
the stem or other parts Thus, in Java, th
having beaten the inflorescences of palms wi
hammers, cut off the flower-stalks, and fix vesse
the liquid which exudes from the wounds

Connected with phenomena of bleeding
exhibited by certain plants, *e g* oat, fuc
frage, etc , which show frequently in the morn
of water, often mistaken for dew, glistening on
or surfaces of the leaves (p 2, Chapter I)
tropical plants, *e g* species of Colocasia, this pl
of *guttation* is so marked that at intervals of a f
drops of water drip like rain from the tips of
In these cases, it is found that the leaves poss
organs, often formed by the modification of stom
as hydathodes [1] In various plants, notably in
saxifrage, the water exuding from the hydathod
carbonate of lime in solution, which, on the e
of the water, is deposited as a white fringe on
of the leaves Certain water-plants, *e g* Ranun
tilis, Callitriche verna, etc , possess very conspic
thodes at the tips of the leaves, which either op
to the exterior or are covered over only by the cu
probable that, in water-plants, these organs serv
of increasing the rate at which water is dischar
leaves, and so of augmenting the supply of

[1] The phenomenon of "guttation" is most easily observed v
is growing under conditions which, whilst favouring absorptio
the roots, hinder rapid transpiration, *e g* in the early morni
moist greenhouse, or, if the plant is kept under a bell glass, in
The excretion of liquid water may be observed in any of
plants —Primula sinensis, Tropæolum majus, Aconitum nap
lum sp , Fuchsia sp , Helleborus niger, Vicia sepium, Tri
Avena sativa, Zea Mays (See list of plants, Appendix)

mineral salts Owing to the fact that many of these plants have submerged leaves, the transpiration of water-vapour does not occur, indeed, in some cases, stomata are not present, and hence the movement through the plant of water containing dissolved salts is likely to be very slow. The explanation of the significance of hydathodes in the case of terrestrial plants may be as follows —During the night, the roots continue to absorb water, but transpiration, as we have already indicated, is considerably reduced The water-courses, and the tissues of the plant generally, become filled with water, and the increasing pressure is relieved by the exit of water through the "water-pores" or hydathodes, which may thus be likened to safety-valves

In concluding our study of the relation of plants to water, we note that, beside effecting the transport of dissolved mineral substances to the leaves, transpiration serves also to prevent the undue heating of leaves exposed to bright sunshine Just as perspiration, evaporating from our bodies, lowers the surface-temperature, so transpiration lowers that of the leaf Finally, the fact that, during bleeding, sugars and other organic substances may be exuded from the vessels, may be taken to indicate that, not only are the vessels the conduits along which water and salts (crude sap) are transported, but also that they may serve, upon occasion, for the transport of "elaborated sap," that is, of plastic food-materials In spring, at all events, when the unfolding leaves are making a heavy demand on other parts of the plant for food-substances, it appears that the demand is met by the discharge of sugar and other plastic food-substances in solution into the vessels through which these substances are transported rapidly, in the transpiration-stream, to the leaves

Before leaving this subject, we demonstrate that transpiration—that is, the regulated process of evaporation of water—is not confined to the leaves As the results of Exp 138 indicate, the shoot-axis may also transpire

167* Microscopic examination of sections across a young shoot shows that stomata are present in the epidermis, and we demonstrate, by means of cobalt chloride paper applied to a portion of a young stem, that the

stomata serve as channels for the escape o
vapour

168 In older stems, e.g. two- or more
branches of trees or woody shrubs (elder, c
stomata are replaced by less regular opening
lenticels, which, as we may show by the cobalt
method, serve for the exit of water-vapour. The
in the elder, etc., may be recognised by the nak
small elongated areas, differing in colour from th
the surface of the stem. That they serve as ch
communication between the external air and th
intercellular spaces of the plant we demonstrate t

169 In summer, cut off a two- or three-year-
of elder or horse-chestnut. Remove from it a p
of leaves and several inches in length. Attach to
a short length of rubber tubing, turn the tubing
and bind it tightly to that on the stem so as t
completely. To the other end of the piece of ste
a thick indiarubber tube (pressure tubing) abo
long. Insert into the free end of the pressure
stout glass tube several feet in length. Make
good, lay the stem in a vessel of water, add wate
the glass tube, and, by squeezing the rubber, driv
air contained in the pressure tubing. Clamp
tube vertically in a retort stand. Pour mercury
glass tube by means of a funnel. Note that, as t
of the mercury column increases, streams of a
escape from the lenticels. Compare with Exp
apply a similar explanation.

170 * Microscopic examination of a cross-s
the superficial tissues of the old stem of elder,
plies the explanation of the behaviour of the le
allowing the escape of gases. Whereas the ou
of the shoot are made up generally of brick-sha
fitted closely together, the lenticels consist of rour
between which are definite intercellular spa
brick-shaped cells are empty, dead, and ha
corky walls. A section through a small piece
cork shows similar layers of brick-shaped ce
cork is used domestically to prevent the e
water and gases. Man, in fact, puts cork to a u

to that to which it is put by the plant The layers of cork which occur in the older shoots of woody plants serve to prevent loss of water by evaporation from the thin-walled, delicate, underlying tissues But a continuous jacket of cork about a branch would not only mean prevention or reduction of loss of water by evaporation, it would also mean prevention or reduction of all gaseous exchange The tissues of the stem would be deprived of oxygen, and, consequently, their growth and activity would be checked The lenticels, like the stomatal openings of the leaf and of the young stem, serve as aerating channels, and hence also as channels for the escape of water-vapour We thus discover that the plant, by developing a 'water-proof" layer of cuticle in the outer walls of its epidermal cells in the young parts (leaves, young shoot), and by forming sheets of cork in or beneath the epidermis of its older stems, contrives to meet two needs, (1) the prevention or reduction of indiscriminate evaporation, and hence the regulation of transpiration, and (2) the provision of aerating channels whereby gaseous exchange between the air and the tissues of the plant is maintained If oxygen is being used by any of these tissues, it is derived from that in the air of the intercellular spaces The oxygen pressure of that air falls When it falls below that of the external air, diffusion of oxygen molecules from the external air to that of the intercellular spaces is set up, and thus the cells abutting on the intercellular spaces receive a constant supply of oxygen Similarly, any gases produced by the cells of the tissues of the plant may escape by diffusion into the outer air

We have a means of verifying the accuracy of the twofold significance of lenticels in relation with transpiration and with gaseous exchange In winter, the plant is, compared with its summer state, at rest The leaves fall, and the buds remain till spring enclosed within hard scale-leaves In such circumstances, the plant has need for but little oxygen, and hence is under no necessity of keeping its aerating channels open Moreover, since, in winter, the soil-temperature falls so low that the root-system is able to absorb but little water, the existence of open passages through which water-vapour may readily escape would be a source

of danger to the plant, leading to its death by c
Therefore, if our interpretation of the two old sig
of stomata and lenticels is correct, we should ex
find that the plant takes steps to put them out o
during winter With respect to the leaves, we kn
in most plants this is so they are, in deciduous tr
out of action altogether by being cast off from the bi
With respect to herbaceous perennials, the prever
loss of water is effected by the most drastic mea
whole plant dies down to the level of the grou
winters underground

171 That the lenticels also are put out of
in winter we demonstrate by repeating, at that
Exp 169 We find then that, in spite of considerat
sure, no air escapes from the lenticels They are

172 * By means of sections we prove that, w
plant is preparing for winter, it produces, in its olde
new sheets of cork below those already in existen
instead of forming lenticels of loose masses of ce
does in spring, it produces a continuous cork
beneath the lenticels as well as elsewhere Thus tr
tion is slowed down and gaseous exchange is redu

It is indeed remarkable that the fall of the
engineered in many plants in precisely the same r
Thus, in the horse-chestnut in late autumn, cells
base of the leaf-stalk begin to divide, forming a
layer of brick-shaped cells These cells divide
to form tiers of cells, which become corky Th
cells form a layer around the base of the leaf-sta
moreover the water-channels running through t
to the blade become blocked The leaf, thus s
from fresh supplies of water, gradually withers
and, at a breath of wind, comes rustling to the
This is facilitated by the formation of an "abscis
on the leaf-stalk side of the corky band It con
a few layers of delicate cells formed by rapid div
a row of cells shortly before the leaf falls Th
layer serves the purpose of healing the woun
venting loss of water, ingress of spores of
producing fungi, etc Each leaf that falls is cut
a surgical operation performed by the plant, a

wound produced is healed in advance Similarly, as a consequence of the formation of cork in the stem, all the tissues external to the cork are cut off from supplies of water, and hence dry, shrivel and crack Trees which produce cork in the surface layers of their stems have thin, smooth bark, those which produce it in their deeper layers have thick, corrugated bark According to the exact mode of development of the cork, the bark is seen to be in sheets as in birch and beech, in lozenge-shaped masses as in elm and oak, and so on

When growth resumes in spring, not only are new leaves formed, but, in many trees, by the growth of the deeper tissues of the stem, the bark is split and torn, and may be cast off Many plants utilise the tissues which constitute the bark for excretory purposes, that is, for getting rid of waste-substances Thus it is that many and varied kinds of materials, some of which are of great value in commerce and medicine, are obtained from the bark of trees (quinine, tannin, hazeline, etc)

Using the nomenclature of p 149, we may say that, in winter, a deciduous tree, leafless and girt in cork, is a xerophyte, in summer, crowned with delicate leaves and with open lenticels, it is a hygrophyte Such plants, which change periodically from the xerophytic to the hygrophytic state are called tropophytes and to the fact that, as soil-temperature falls, absorption of water decreases below the amount necessary to make good the loss due to transpiration is to be ascribed the wonderful series of changes which mark the preparation of the plant for passing the winter The subject is an alluring one, but we cannot follow it further now

173 The changes of some common tree should be followed throughout the year and records of the dates of bursting into leaf, of closing of the lenticels, of cork formation, etc , should be made, and the records compared with meteorological records, particularly with those of soil temperatures

CHAPTER XI

THE origin of the carbon compounds contained in plant materials from which the plant constructs these comp part played by chlorophyll grains (chloroplasts) in the p process the energy by which the process is carried on of carbohydrates from the leaves to other parts of the synthesis of organic nitrogen compounds by the plant

BEFORE we embark on the last stage of our en the mode of nutrition of plants, we will review conclusions to which our experiments have led

Sand- and water-cultures have served to de that certain mineral substances are essential to p also, that all the elements required by the pl nutrition are, with the exception of carbon, de the soil in the form of water and mineral the water and mineral salts absorbed by th certain amount passes by osmosis from cell to thus satisfies local needs, but the great bulk way of the transpiration current to the leaves water is transpired and the mineral substance behind Thus the green cells of the leaves re stant supplies of mineral substances Since the salts do not accumulate indefinitely in the le since also the elements which they contain be stituents of complex organic bodies, such as p is evident that the mineral salts, in serving for undergo chemical change Therefore, they regarded, not as food-substances, but as raw used by the plant in the manufacture of food-s Similar considerations convince us that the carbo ing organic substances occurring in the plant a

result of processes of manufacture carried on by the plant, and that the carbon which finds a place in these organic compounds is derived from external sources

It is our object in this chapter to discover what we can of the nature of this manufacturing process, and we commence by enquiring into the source whence is derived the raw carbon-containing material used in the manufacture of organic compounds

The problem is simple We know that a plant may grow and that the amount of its carbon-compounds may increase, although there may be no compounds of carbon present in the soil Therefore, the air is the source whence the plant derives its carbon It must, however, be admitted that this does not appear, at first sight, to be very probable For, on the one hand, the amount of combined carbon contained in a plant—a tree, for example—is very great, on the other hand, the only carbon-containing constituent of pure air, carbon dioxide, makes up but a minute fraction (·03%) of the total volume of the atmosphere It is doubtless these facts which made botanists, down to comparatively recent times, slow to accept the result of the earlier experiments which pointed to the air as the source of carbon to the plant They preferred to adhere to the old "humus theory," which taught—seemingly on good grounds—that the organic compounds of carbon in the soil are the sources whence the green plant obtains its supplies of this element They knew that plants flourish when provided with a plentiful supply of organic carbon-compounds, when, for instance, the land is richly manured, they noticed that soils deficient in these substances support but poor crops, and it seemed to them a breach of common-sense to be asked to believe that the air, with only some three parts in 10,000 of carbon-dioxide, could provide the large quantities of carbon which are contained in plants A more thorough consideration of the facts shows us that, though the *percentage* of carbon dioxide in the atmosphere is but small, the actual quantity contained in that vast ocean of air is enormous Moreover, this quantity is augmented constantly Every fire that burns, every plant or animal that respires, and every organic substance which undergoes decay,

produce carbon dioxide, and discharge it into the atmosphere

But, after all, experiment is better than argument, and we proceed, therefore, to put the matter to experimental proof

If the carbon dioxide contained in the air is the raw material used by the plant in the manufacture of organic compounds, then we shall expect to find that an adult plant supplied with air, from which the carbon dioxide has been removed, ceases to manufacture organic carbon compounds Since, as our studies of germination have shown, organic carbon-compounds, such as sugar, serve for the nutrition of the plant, it follows that, if there are no stores of organic carbon-compounds present by preventing the plant from manufacturing these compounds, we reduce it to a state of starvation To carry out the experiment, we proceed as follows —

174 Take two approximately equal, actively-growing young sunflower or dwarf bean plants raised in small pots label them A and B, cut off a piece about half an inch square of one of the older leaves of each plant Having watered the plants, place them in the dark At daily intervals, cut off similar samples Keep the samples separate, and immediately after they are cut off, plunge them for a minute into boiling water to kill them Place the pieces in wide specimen tubes containing methylated spirit Label each tube with the letter A or B and the date on which the piece it contains was cut off Cork the tubes and expose them to bright sunshine After a piece has been in a tube for 24-48 hours, take it out, observe that it is brittle and colourless, and rinse it with water Place each sample separately in a white saucer, and pour over it a solution of potassium iodide iodine, to which has been added a strong solution of chloral hydrate (Appendix A) Observe that, as indicated by the iodine reaction, when the plants are maintained in the dark, the starch which is contained in their leaves gradually decreases in amount until, after one or more days, it disappears altogether When this has happened, the plants are ready for use They should, however, be kept in darkness till the apparatus now to be described has been prepared

175 Having obtained two large bell-jars—(the cloche

(Appendix A) used in "French Gardening" serve admirably), take one of them to a carpenter and get him to make the following:—A circular, wooden base-board about an inch thick and of a diameter about two inches larger than that of the rim of the bell-jar. The base-board must be of one piece, and should be varnished. Three, 3-inch cubes of wood to serve to raise the base-board above the level of the table or ground. Instruct the carpenter to cut on the base-board a circular groove, about $\frac{3}{8}$ inch in depth and $\frac{1}{2}$ inch wide, of such diameter that the rim of the bell-jar fits comfortably into it, and to bore a round hole 1-1$\frac{1}{2}$ inches diameter, at a distance from the groove about equal to one-third of the diameter of the circle described by it. The edge should be circular and smooth since a rubber cork is to be inserted in the hole.

Bring the apparatus into the laboratory, and select a glass tube of such a size and shape that, when it is in position under the bell-jar, its wide end is an inch or more from the top of the latter, and its narrow end projects below the bottom of the base-board, but clears the table by about 2 inches. A cylindrical separating funnel with a narrow stem serves the purpose (Appendix A). Push a small plug of cotton wool to the bottom of the wide end of the tube, and fill the latter with soda-lime—a substance which absorbs carbon dioxide. Insert the stem of the absorption tube into a rubber cork which is large enough to fit tightly into the hole of the base-board. Fix the rubber cork in position, make a good joint, attach to the end of the stem which projects beneath the board a piece of rubber tubing, and close the latter with a clamp. Set up the board in a well-lit place—preferably in a sheltered position in the open-air but screened from direct sunlight. Bring quickly one of the plants (A) from the dark room. Make *rapid* measurements of the height of its stem and the size of its smallest leaves (this need only take a minute or so). Stand the plant on the board, place the bell-jar in position, and cover the bell-jar with a double fold of black Italian cloth in order to protect the plant temporarily from the light. Having melted enough wax-mixture (Appendix A) for the purpose, pour it into the groove so as to seal the bell-jar (or soft putty may be used). Bring the second plant from the dark, measure

its stem and youngest leaves Cover it loosely bell-jar. This second apparatus serves as a Remove the black cloth from the first bell-jar, unc rubber tube so that air may now enter the bell-jar the absorption tube We thus have the two plan fairly similar conditions, except that one rece deprived of carbon dioxide, the other ordinary air the plant which is exposed to ordinary air a definite increase both in height of stem and the younger leaves, estimate and record the noting also the number and size of any leaves it n unfolded since it was put under the bell-jar the wax from the edge of the other bell-jar, take plant, cut off one of its older leaves, and, having left in a dark place, determine that the plant ha but little or not at all, and that it has devel new leaves Make these observations as qu possible As soon as they are made, cut off from the control plant Before examining the cu place the plants in the dark Make a deep one of the two isolated leaves in order that be distinguished from the other, and test th for starch by the iodine method Observe that taken from the plant which was exposed to ordi gives a well-marked, blue starch reaction, and leaf of the plant which was deprived of carbon gives no starch reaction Bring the plants from room into bright sunlight At intervals of five minu samples of the leaves of the plant which was under t bell-jar, and, by means of the iodine test, demonstr within ten minutes or so of the time at which plan exposed to the light, starch makes its appearanc leaves, and that the amount of starch—as judge depth of blue colour increases as time goes on further, that the plant, the development of wh checked completely when it was in air devoid o dioxide, may begin again, in the course of a day o increase in size, and to unfold new leaves

We learn from this series of experiments that

(1) The leaves of a green plant, grown under conditions, contain starch

(2) Starch disappears from the leaves of a plant kept in darkness

(3) Starch reappears very quickly and in increasing quantities when the plant is brought again into the light and exposed to normal conditions

(4) If a plant is deprived of carbon dioxide, no starch appears in the leaves, even though it is exposed to a good light

(5) In the absence of carbon dioxide, the growth and development of the plant are checked

From the results of our experiments on the germination of seedlings, we know that reserve starch stored in the seed serves to provide the seedling with carbohydrate food-material Hence it is probable that the starch which makes its appearance in the leaves of plants grown in the light in ordinary air serves also to provide for the nutrition of the plant Since, moreover, starch does not appear in the leaves of plants grown in air deprived of carbon-dioxide, it is probable also that carbon-dioxide serves as the raw material from which carbohydrate, which appears in the leaf as starch, is manufactured If this is so, the leaves—and other green parts of a plant—are the seat of a manufacturing process which is of fundamental importance not only to the plant itself, but also indirectly to animals, all of which obtain their food ultimately from plants But since the leaves of plants kept in darkness do not form starch—indeed, as we have seen, this substance actually disappears from them under these conditions—it follows that, if starch is manufactured by the leaves of plants, light plays an essential part in the process Now, it is easy to demonstrate that the starch which appears in the leaves of plants exposed to the light is actually manufactured in the leaves, and is not carried thither in the form of sugar from other parts of the plant

176 For this purpose, take a well-grown pot-plant (bean, clover, etc) and keep it in the dark till its leaves—as determined by tested samples—contain no starch Then detach one or more leaves from the plant, place their petioles in distilled water and expose the leaves to the light After an hour or so, on applying the iodine test (cf Exp 174), we discover that starch has made its appear-

ance in the isolated leaves. Inasmuch as the are isolated from the plant, the starch which a them cannot be derived from substances trans the leaves from other parts. Therefore, either have been manufactured from raw materials some substance, such as sugar, already prese isolated leaves. Since, however, as Exp. 174 ha starch does not appear in leaves which, after they depleted of this substance by a sojourn in the brought into the light and confined in a ves which carbon dioxide is excluded, we conclude starch which appears in the illuminated, isolat ance is the result of a process of manufacture raw material, of which carbon dioxide is one ployed. That this is the only conclusion open demonstrate further by showing that the dark contains little or no sugar. Thus

177 Take two lots of leaves, one from the plant of Exp. 175 and one from a similar plant become adapted to a good light for some hours. Cu pieces under water, pound each lot separately in with a little water, transfer each mass to a bea and filter. Test the filtrate for sugar. Obs the dark-kept leaves give no, or at most a slig reaction, and that the light-exposed leaves giv marked sugar reaction. We thus learn that n starch produced when the green parts of le exposed to light, but that sugar also is forme this sugar and starch can only have been from raw materials (carbon dioxide and w may speak of their formation as a synthesis o ups, and since light is essential for their formation describe the process as one of *photosynthesis* he dicate. For much as it is by this process that obtains its supplies of organic carbon-compo photosynthetic process is termed sometimes th *assimilation of carbon*, or of carbohydrates.

The question now presents itself. Have the g ability the power of photosynthesis, or is it possess the colourless cell of plants? The answer we the following observations.

178 ' Cut transverse sections through a leaf (beech, privet, sunflower, etc) gathered during the day-time Mount the sections in water Observe that the green colour of the leaf is due to the presence of vast numbers of green granules (chlorophyll grains or chloroplasts), lying in many of the cells Note that the ordinary cells of the outer layer (epidermis) of both upper and lower sides of the leaf contain no chlorophyll grains, but that chlorophyll grains are present in the guard-cells of the stomata and in the vertical rows of cells (palisade parenchyma) beneath the upper epidermis as well as in the less regular groups of cells (spongy parenchyma) which lie beneath the palisade parenchyma and extend to the lower epidermis Observe also the large intercellular spaces between the cells of the spongy parenchyma Run in potassium-iodide, iodine, chloral hydrate solution, and observe that starch grains are present in the chlorophyll-containing cells (including the guard-cells of the stomata) but are absent from the colourless epidermal cells Note the stained starch grains attached to the chloroplasts

179 Then obtain one or two leaves of a variegated plant the foliage of which is thin and delicate (variegated maple, Abutilon, etc) Either photograph the leaf or make an accurate drawing, *e g* a tracing of the outlines of its green and colourless parts Test the leaf for starch by the iodine method and, by comparing the leaf with the original photograph or drawing, determine that the original green areas are stained blue, and hence contain starch, whereas the colourless areas of the leaf are not stained blue—that is, contain no starch We thus learn that starch occurs only in those cells of the leaf which contain chlorophyll Hence we infer that the chloroplasts play an essential part in the photosynthesis of carbohydrates

But, as we learned in Exp 16, starch may occur in colourless cells, *e g* in cotyledons of seeds, in cells of woody tissues, in tubers such as the potato, and so on Moreover, since organs such as potato tubers are formed and remain underground, the starch which occurs therein does not, like that in leaves, require light for its formation. The well-known fact that green plants cannot live and in-

crease except when growing in the light, combined with results of these observations, leads us to conclude that reserve starch of underground organs and other colourl plants is not synthesised from inorganic materials in th storage organs, but is derived from the carbohydra manufactured by the leaves and other green parts of plant On this view, a green leaf not only manufactu carbohydrates to satisfy its own needs, but also supp carbohydrates to the colourless cells of the plant.

This conception of the leaf as a factory of car hydrates for the plant as a whole, helps us understand the comparative rapidity with which sta may disappear from the leaves of plants kept in the da We can imagine that the starch, accumulated in leaves, undergoes a change similar to that which starch, accumulated in a bean cotyledon, undergoes dur the germination of the bean, namely, a conversion by agency of diastase into sugar, and just as the sug formed in the cotyledon passes away to nourish, or accu late in, the embryo, so that formed from the starch the green leaf travels *via* the petiole to the shoot, whe it is distributed in all directions, to serve either for nutrition of growing cells or to form the reserve sta stored in the various tissues

In order to confirm the truth of this conjecture, require, firstly, to prove that the green plant possesses power of converting sugar into starch, and secondly obtain evidence that the starch which is found in the gr leaf as the result of the photosynthetic process may away in some soluble form, such as sugar, from the to other parts of the plant

180 To demonstrate that a plant is capable converting sugar into starch we keep a plant, Elodea, in the dark till all starch has disappeared f its leaves Then, having prepared a 3% solution glucose, cut off several of the starch-free leaves float them on the surface of the sugar solution in sau and keep them in the dark After a day or two, apply iodine test, and observe that starch has made its appear in the leaves

181.* By treating sections of the leaves with iod

and examining microscopically, we demonstrate that the starch grains occur in close association with the chloroplasts

Thus we learn (1) that a plant has the power of converting sugar into starch, and (2) that, in the green leaf, this conversion is effected by the chloroplasts A chloroplast, therefore, appears to have the power of manufacturing starch in two ways either by photosynthesis or by acting on sugar The former mode of manufacture occurs only in light, the latter may occur in darkness The evidence in favour of the view that the starch which accumulates in the leaves of plants exposed to sunlight may be translocated in a soluble form, we obtain thus —

182 Cut off three similar leaves from a plant, *e g* Spar-mannia, which has been exposed for some hours to a good light Put two of the leaves with their leaf-stalks in water in the dark, and, at the same time, place the plant itself in the dark Test the remaining detached leaf for starch After twenty-four hours, cut off one or more of the leaves of the dark-kept plant, test them and also one of the detached, dark-kept leaves for starch Repeat the experiment after forty-eight hours, using the remaining, dark-kept, detached leaf and one or more leaves which have remained attached to the dark-kept plant Observe that the starch disappears more rapidly from the leaves which remained attached to the plant during its exposure to darkness than from the detached, dark-kept leaves Similarly, demonstrate by using starch-free leaves of a dark-kept plant that starch may accumulate in a detached leaf (with its petiole in water) brought into the light just as in a similar leaf which is attached to the plant and exposed to light The latter part of the experiment demonstrates that the activities of the detached leaf have not been impaired by its removal from the plant, and hence the only explanation of the persistence of starch in the detached leaf in the former part of the experiment is that carbohydrate cannot escape from the detached leaf We conclude, therefore, that, in the normal plant, the carbohydrate produced photosynthetically in the leaf, passes away in the form of sugar to supply the needs of the whole plant

Now, when we consider the extraordinary rapidity with

which the leaf photosynthesises carbohydrate when exp to light (Exp 175), and also the narrowness of the stalk, some of the tissues of which, e.g. vessels and trach of the wood, are concerned with other work, we can un stand that the rate at which a leaf manufactures c hydrate may be greater than the rate at which the pr of this manufacture can pass from the leaf to the o parts of the plant This being the case, there is a gl carbohydrate in the leaf Such an accumulation w undoubtedly—unless it could be got out of the way- pede the action of the machinery involved in the man turing work Thus the idea suggests itself that machinery must either cease working, or that the exce photosynthesised carbohydrate must be stored tempor in the leaf in some form in which it does not interfere the working of the machinery Now, an insoluble, i fusible, solid substance is less in the way than a sol diffusible substance Starch belongs to the former and sugar to the latter type Hence we may pose that, if sugar is the first product of p synthesis, and if it is produced by the green leaf f than it can be conducted away from the leaf, the e may be stored in the form of starch The chloro machinery must perforce be idle during the night, so whereas the manufacturing process can go on only d the hours of daylight, the work of distribution ca carried on night and day The hours of daylight a too brief, as it is, for the green leaf to manufacture en carbohydrate to satisfy the needs of the growing plant supply it with food-material and to allow it to accum large stores of starch in reserve organs, seeds, etc would be bad business, therefore, for the photosyn process to be shut down merely because the product not be distributed fast enough, it would be good bu if the leaf could store its excess of manufactured ma temporarily, so that the chlorophyll machinery migh full time Such considerations suggest to us tha starch which appears in the leaf is not the direct prod photosynthesis, but is—as it is in seeds, etc.—a re form, in which the excess of photosynthesised carbohy is stored temporarily

Let us ascertain if the facts support this hypothesis In the first place, we have proved already that sugar as well as starch makes its appearance in the leaves when a dark-kept plant is exposed to light (Exp 181) Hence sugar has at least as much claim as starch to be regarded as the immediate product of photosynthetic activity In the second place, starch is, as we know, a more complex body than are sugars —

$$\text{Thus starch} = (C_6H_{10}O_5)_x$$
$$\text{glucose} = C_6H_{12}O_6$$
$$\left.\begin{matrix}\text{maltose}\\ \text{and cane sugar}\end{matrix}\right\} = C_{12}H_{22}O_{11}$$

and it would seem more likely that the less complex body is produced first

183 Test for starch and sugar the leaves of such plants as iris, onion, Scilla, which, after having been kept for a few days in the dark, *e g* by covering with an inverted flower-pot, have been exposed to the light for some hours Observe that, whereas sugar is present, the leaves contain little or no starch We thus learn that, even in leaves in which starch is formed as a result of photosynthesis, sugars are also present, and that, in other plants, the products of photosynthetic activity are sugars and not starch

We may conclude, therefore, that some form or other of sugar is the immediate, carbohydrate product of photosynthesis Of this sugar, some may be used for local nutritive purposes, some may be used locally for respiration, but the bulk is translocated from the leaves to other parts of the plant Of the sugar thus translocated, part is used immediately for nutritive or respiratory purposes, and part serves one or other of these purposes ultimately, but undergoes, in the meantime, a change into the reserve form, starch So, too, the excess of sugar produced over that translocated accumulates in the leaf during the day, and is converted into the more convenient storage form of starch, which, however, is changed by diastase back again into sugar as

soon as the road is clear for the passage of this substance Thus the green leaf is, during the day, the seat of carbohydrate synthesis, and thus, night and day, there passes from the green cells to all parts of the plant a constant osmotic stream of sugar Just as the excess of production over local consumption and over translocation leads to an accumulation of starch in the leaves, so an excess of supply over consumption in any part leads to like storage in the form of starch, and thus it is possible for reserve-organs to assemble large quantities of this substance

But one point still awaits explanation, viz —How is the conversion of sugar into starch effected?

We know that the starch in the leaf makes its appearance in the form of grains attached to, or imbedded in, the chloroplasts We know, on the other hand, that reserve organs, underground tubers, etc, contain no chlorophyll grains How then do the cells of such organs contrive to convert sugar into starch? Now, we have learned ahead that most plants grown in the dark produce leaves which contain no green colouring matter, and we may ask ourselves the question whether such dark-grown plants are able to store starch in their leaves? This question is, of course, capable of being solved experimentally

184 * In order to do this we raise seedlings of Phaseolus or potato in darkness Without stopping now to consider the peculiar features presented by the dark-grown etiolated plants, we proceed at once with our experiment by testing leaves for starch Having shown that the leaves contain no starch, cut off several leaves, float them on a 10-20% glucose-solution in the dark At daily intervals, apply the starch-test to one of each of these leaves, and also to others which have remained attached to the plant in the dark Having demonstrated that starch is present in the leaves which have floated on sugar-solution and not in the others, cut sections of the former, mount in water, run in iodine solution, and note that the starch-grains are associated each with a yellow brown stained granule Bring the plants from darkness into a good light Soon after a distinct greenish colour is visible in the leaves, (a matter of an hour or so) cut sections of a leaf of each plant, observe the chloroplast

and run in iodine; note that the starch-grains are attached to the chloroplasts, and hence conclude that the chloroplasts of the green, light-grown plant are represented in the colourless, dark-grown plant by colourless granules, which we may call *leucoplasts*. Evidently the leucoplast is a starch-former, and is able to manufacture starch from sugar, and the chloroplast is a more efficient starch-former, for not only is it able to manufacture starch from sugar, but also to manufacture sugar from inorganic materials.

185 [1] By microscopic examination of young tubers of potato, etc., demonstrate that the starch-storing cells contain leucoplasts, and that the starch-grains are each formed by a leucoplast.

186 Expose potato tubers to a good light, and observe that, in course of time, they become green, that is, their leucoplasts develope, like those of an etiolated leaf exposed to light, the green colouring matter, chlorophyll, which permeates the chloroplast as water permeates a sponge.

We conclude, therefore, that specialised protoplasmic structures, leucoplasts, may occur in the colourless cells of a plant, that they have the function of manufacturing reserve carbohydrate (starch) from plastic carbohydrate (sugar), that the chloroplast is a leucoplast in which green colouring matter, chlorophyll, is developed, and that the chlorophyll confers on the chloroplast the power of manufacturing sugar—in the presence of light—from raw inorganic materials.

187 [4] It is interesting to note also that the green chloroplasts may themselves undergo a change in colour, as, for example, in the petals and fruits of certain plants, which become brightly-coloured as they ripen. Microscopic examination of various stages shows that such colours are due to small irregular bodies, chromoplasts (or chromatophores), which are derived from chloroplasts. In other cases, however, bright colours, *e.g.* the purple of the copper beech, the colours of the petals of the sweet pea, violet, etc., are, as we determine by the microscopic examination of sections of these objects, and as we have seen in the case of the beetroot, due to pigments dissolved in the cell-sap.

We may express our conclusions as to chl
leucoplasts and chromoplasts thus —

plastids	leucoplasts, chloro chromoplasts,
leucoplast and chlorophyll	= chloroplast,
chloroplast in which chloro phyll has undergone chemical change and is replaced by a yellow or red pigment	chromoplast (chrom

We must return now to consider more cl
chemistry of the photosynthesis of sugar, and
which light plays in this process. So far, all that
is that, during photosynthesis, carbon dioxide is
and sugar formed. When we consider the form
simple sugar (*e.g.* glucose) $C_6H_{12}O_6$, it become
that, in the process of photosynthesis, some s
which serves as the source of hydrogen must, toge
carbon dioxide, take part in the reaction. The o
source of the hydrogen which enters into the su
cule is water. But if we assume that the hydrog
photosynthesised sugar is derived from water,
carbon dioxide and water together to produce su
must first be a deoxidation or reduction of one or
these substances. Assuming this, we may sym
reaction thus: $6CO_2 + 6H_2O = C_6H_{12}O_6 + 6O_2$.

If, therefore, our assumptions are correct,
expect to find that, whenever photosynthesis goes
gen is liberated. In order to ascertain whether t
case, we proceed as follows:

188 Take several green shoots of some comm
plant, *e.g.* Elodea canadensis, tie them loosely
put them, with their cut ends upwards, inside
inverted funnel, the mouth of which just fit
large beaker full of water. Fill a test t
water, and closing it with the thumb, invert it
stem of the funnel, which projects upward near
level of the water in the beaker. Thus, any gas
by the submerged shoots passes up through the s
collects in the test tube. Bring the apparatus int
light, and observe that, at once, bubbles of gas are

from the shoots and rise in the test tube Allow the experiment to go on until the test tube is nearly full of gas This may take several days Having prepared a glowing splinter, *e g* by lighting a match and blowing it out, lift the tube from the water, plunge into it the glowing splinter and observe that the latter bursts into a bright flame, whence we infer that the gas in the tube consists largely of oxygen By more exact methods it may be demonstrated that, as is required by our formula, the volume of carbon dioxide absorbed during photosynthesis is equal to the volume of oxygen evolved We thus conclude that a step in this process consists in the reduction of carbon dioxide and water, and we may picture this step thus —

$$\left.\begin{matrix} C \\ O \end{matrix}\right\} + \left\{\begin{matrix} H \\ H \end{matrix}\right. = H\ COH \text{ (formaldehyde)}$$
$$\left.\begin{matrix} O \end{matrix}\right| \quad \left|\begin{matrix} O \end{matrix}\right. = O_2 \text{ (oxygen)}$$

On various grounds it is believed that this substance H COH (formaldehyde) is actually the first product of photosynthesis, and that its molecules condense to form sugar thus —$6H\ COH = C_6H_{12}O_6$ In any case, we recognise that in photosynthesis the reaction takes place in several stages, and that the first stage consists in a reduction process, which is made evident by the evolution of oxygen

Water-plants such as Elodea serve also for investigations into the conditions under which photosynthesis takes place

189 Select a healthy shoot of Elodea, make a clean cut across its stem, wipe the cut end gently with blotting-paper, and brush a layer of collodion over it When the collodion has set, make a small hole in the film by means of a needle, tie the shoot, cut end upward, to a glass rod, and submerge it in a large beaker of water Using the rate at which bubbles escape from the cut end as an index of photosynthetic activity, determine the influence of light-intensity on the rate at which this process goes on This may be done by counting and comparing the rates at which bubbles are given off when the apparatus is placed at varying distances from a well-lit window A better method consists in the use of an incandescent light